



Hydroeconomic modeling to support integrated water resources management in China

Daidsen, Claus

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

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Citation (APA):
Daidsen, C. (2015). *Hydroeconomic modeling to support integrated water resources management in China*. Technical University of Denmark, DTU Environment.

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Hydroeconomic modeling to support integrated water resources management in China



Claus Davidsen

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Claus Davidsen

PhD Thesis
June 2015

DTU Environment
Department of Environmental Engineering
Technical University of Denmark

Claus Davidsen

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management in China**

PhD Thesis, June 2015

The synopsis part of this thesis is available as a pdf-file for download from the
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Address: DTU Environment
Department of Environmental Engineering
Technical University of Denmark
Miljoevej, building 113
2800 Kgs. Lyngby
Denmark

Phone reception: +45 4525 1600

Fax: +45 4593 2850

Homepage: <http://www.env.dtu.dk>

E-mail: info@env.dtu.dk

Printed by: Vester Kopi
June 2015

Cover: Torben Dolin

Preface

The work presented in this PhD thesis was conducted at the Department of Environmental Engineering of the Technical University of Denmark (DTU) and the Institute of Geographic Sciences and Natural Resources Research at the Chinese Academy of Sciences (CAS) from 1 September 2011 to 31 March 2015. As a part of the PhD, 12 months were spent in Beijing, China, at the Chinese Academy of Sciences. Associate Professor Peter Bauer-Gottwein from DTU was the main supervisor, Professor Emeritus Dan Rosbjerg from DTU, Professor Xingguo Mo from CAS and Professor Suxia Liu from CAS were co-supervisors.

The research was funded by the Sino-Danish Center for Education and Research (SDC), Aarhus, Denmark and the Department of Environmental Engineering of the Technical University of Denmark, Kongens Lyngby, Denmark.

The PhD thesis encompasses three scientific papers. These will be referred to in the text by their paper number written with the Roman numerals **I-III**. The first has been published in *Journal of Water Resources Planning and Management* (ASCE). The others have been submitted, but not yet accepted.

- I** Davidsen, C., Pereira-Cardenal, S.J., Liu, S., Mo, X., Rosbjerg, D., Bauer-Gottwein, P., 2014. Using stochastic dynamic programming to support water resources management in the Ziya River basin. In press.
- II** Davidsen, C., Liu, S., Mo, X., Rosbjerg, D., Bauer-Gottwein, P., 2015. The cost of ending groundwater overdraft on the North China Plain. Manuscript.
- III** Davidsen, C., Liu, S., Mo, X., Rosbjerg, D., Holm, P.E., Trapp, S., Bauer-Gottwein, P., 2015. Hydroeconomic optimization of reservoir management under downstream water quality constraints. Manuscript.

Three field reports (**IV-VI**), which document the findings from field trips to the case study area, are included as appendices:

IV Field report 1: June 2012

V Field report 2: July 2012

VI Field report 3: March 2013

In this online version of the thesis, the three papers (**I-III**) are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from:

DTU Environment,
Technical University of Denmark,
Miljøvej, Building 113,
2800 Kgs. Lyngby,
Denmark,
info@env.dtu.dk

Acknowledgements

First of all, I would like to thank my supervisor Peter Bauer-Gottwein for being such an excellent supervisor. You have always been available to assist and encourage me, and your great dedication has been extremely inspiring. Thanks also to my co-supervisor Dan Rosbjerg and to my co-authors Peter E. Holm and Stefan Trapp for many interesting discussions and for guidance throughout the project.

I am very grateful to the Sino Danish Center for funding the research and to Otto Mønsted's Fond for support to my stay in Beijing.

My one year research stay at the Chinese Academy of Sciences was extremely fruitful and I would like to thank my two kind Chinese co-supervisors Suxia Liu and Xingguo Mo for making me feel welcome in their research group and for sharing their experiences from the Ziya River Basin with me. Also great thanks to Yalu Song and Zhonghui Lin for your great assistance.

Thanks also to all the people I met in Beijing. Special thanks to Lars Skov Andersen for kind guidance and inspiration. Thanks to all the SDC students which kindly adopted me to their little community and gave me so many wonderful memories from Wudaokou: Jan Ole, Mette, Majken, Grith, Casper Eskild, Gro and many more. Thanks to Saqib and Dirk for many great times.

Thank you to the students which have been involved in the project. Silje and Jacob for assisting with the method development early in my PhD, Kristina for the amazing field trip and her dedicated work with the groundwater model and Leifur and Takumi for great work on developing the method.

I would also like to thank all of my colleagues at DTU Environment, members of the cake club, the butter club and the lunch team. Special thanks to my office mates and office neighbors which have turned every day into something special: Claire, Silvio, Pernille, Filippo, Raphael, Sanne, Ida, the Julies, Klaus, Biao, Mkhuzo, Kawawa, Aaron, Bentje and Maria. Thanks also to Hugo for your dedicated work and for patiently introducing me to the world of UNIX and HPC.

Thank you to Sidsel for your love and support and to my brother and sister for always being there. Thanks to my parents for your love and great inspiration.

Summary

The North China Plain is a 320,000 km² alluvial plain with a population of more than 200 million people, that stretches across the Hebei, Henan, Beijing, Tianjin and Shandong provinces. The plain is an economic hotspot and is extensively used for irrigation agriculture and heavy industries. Population growth and rapid development of the Chinese economy have increased water scarcity and put the natural water resources and aquatic ecosystems on the North China Plain under pressure. Dry rivers, rapidly decreasing groundwater tables and heavily polluted surface water bodies are consequences of the growing demand for water to irrigation, industrial and domestic uses. As a response, the Chinese authorities have launched the 2011 No. 1 Central Policy Document, which set targets related to water scarcity and water quality and marks the first step towards sustainable management of the Chinese water resources. In this context, the PhD study focused on development of approaches to inform integrated water resources management to cope with multiple and coupled challenges faced in China.

The proposed method is to formulate river water management as a joint hydroeconomic optimization problem that minimizes basin-wide costs of water supply and water curtailment. Water users are characterized by water demand and economic value, turning the complex water management problem into a single objective cost minimization problem. The physical system and management scenarios are represented as constraints to the optimization problem, which was solved using a variant of stochastic dynamic programming (SDP) known as the water value method. This method determines and stores shadow prices of water for all system states.

Three different method implementations to the Ziya River, a complex Chinese river basin on the North China Plain, were used to assess water conflicts and interactions between water users and ecosystems. To overcome the curse of dimensionality associated with SDP, the multiple surface water reservoirs were aggregated to a single reservoir. Natural runoff upstream the reservoirs was estimated with a simple rainfall-runoff model based on the Budyko framework and auto-calibrated with measured discharge. The monthly serial correlation was described by a Markov chain and the estimated runoff used as stochastic input.

The first method used a simple linear and convex formalization of the management problem with a single surface water reservoir state variable. A comparison of different management scenarios was used to evaluate how the South-to-North Water Transfer Project will impact optimal water resources management. Scenarios with unregulated groundwater pumping at realistic pumping costs verified that the water users will keep pumping until all water demands are fulfilled.

The second implementation introduced a groundwater aquifer state variable, and linked groundwater drawdown to pumping costs. Non-convexity and non-linearity caused by these head-dependent pumping costs were accommodated with a hybrid genetic algorithm and linear programming formulation. Besides regional drawdown, local drawdown cones estimated with the steady state Thiem solution were included. This enabled analysis of dynamic groundwater and surface water interactions. The results showed that the groundwater aquifer buffered the system and allowed overdraft in dry years in return for increased recharge in wet years. Further, cost-effective recovery of an overdrafted groundwater aquifer was demonstrated.

The third implementation assessed interactions of water resources and water quality management. Biochemical oxygen demand (BOD) was used to represent water quality, and water uses were associated with BOD generation and BOD reduction treatment costs. Constraints on downstream river water quality were included as dissolved oxygen, computed with the Streeter-Phelps equation. Nonlinear constraints were overcome with the hybrid genetic algorithm and linear programming formulation. Costs of compliance with the different Chinese water quality standards were found to be relatively small compared to the water scarcity costs found in the second study. In contrast, the optimal management was highly affected, and allocations were shifted between the users as the model utilized the surface water for dilution.

The developed methods were successfully used to demonstrate how hydroeconomic modeling can guide optimal water management for complex systems. The method is highly flexible and can be applied to systems which can be formalized as up to two reservoir state variables. Linearity and convexity reduce the computation time, but are not required to solve the problem. Cost-effective management can be found across traditionally separate disciplines, and this method thereby represents the type of integrated assessments needed in the context of the China 2011 No. 1 Central Policy Document.

Dansk sammenfatning

Den nordkinesiske slette er en 320.000 km² alluvial slette, med en befolkning på mere end 200 millioner mennesker, som strækker sig over provinserne Hebei, Henan, Beijing, Tianjin og Shandong. Sletten er økonomisk vigtig for Kina og er i stort omfang udnyttet til vandet landbrug samt tung industri. Befolkningstilvækst og den hurtige udvikling af den kinesiske økonomi har øget manglen på vand og sat de naturlige vandressourcer og økosystemerne på den nordkinesiske slette under pres. Udtørrede floder, faldende grundvandsspejl og kraftigt forurenede overfladevand er konsekvenser af det voksende behov for vand til markvanding, industrier og husholdninger. For at modsvare denne udvikling har de kinesiske myndigheder lanceret the 2011 No. 1 Central Policy Document, som markerer første step imod en bæredygtig forvaltning af Kinas vandressourcer ved at sætte målsætninger indenfor vandmangel og vandkvalitet. Dette PhD studie har i denne sammenhæng fokuseret på at udvikle nye metoder til integreret vandressourceforvaltning, der kan håndtere de mange og ofte koblede udfordringer i Kina.

I den foreslåede metode er forvaltningsproblemet beskrevet som en koblet hydrologisk-økonomisk optimering, hvor de samlede omkostninger fra vandforsyning og vandmangel minimeres. Brugernes af vand er karakteriseret ved deres behov for vand samt deres økonomiske gevinst af vandet, hvormed det komplekse forvaltningsproblem kan løses alene ved minimering af omkostningerne. Det fysiske system, samt forskellige forvaltningsscenarier, er repræsenteret som begrænsninger for en optimering baseret på en udgave af stokastisk dynamisk programmering (SDP) kendt som vandværdi-metoden. Her findes vandets skyggepris for alle kombinationer af systemets tilstande.

Gennem tre forskellige implementeringer i Ziyaflodens opland, et komplekst afstrømningsområde på den nordkinesiske slette, analyseres konflikter og samspil mellem brugere af vand og økosystemer. For at overkomme *curse of dimensionality*, som er en velkendt begrænsning ved SDP, aggregeres de mange reservoirer i området til et enkelt. Naturlig afstrømning opstrøms reservoirerne blev estimeret med en simpel hydrologisk model baseret på Budyko-metoden og autokalibreret til målt vandføring. Overgangssandsynligheden mellem månederne blev beskrevet med en Markov-kæde og den estimerede afstrømning anvendt som stokastisk variabel i modellen.

I den første metode blev en simpel lineær og konveks formalisering af forvaltningsproblemet benyttet. Et enkelt overfladevandsreservoir blev benyttet

som tilstandsvariabel. En sammenligning af forvaltningsscenarier blev benyttet til at kvantificere syd-til-nord vandprojektets indflydelse på optimal vandresourceforvaltning. Scenarier med realistiske pumpeomkostninger uden regulering af grundvandspumpningen bekræftede, at brugerne vil fortsætte med at pumpe vand, indtil deres behov er dækket.

I den anden metode muliggjorde en ekstra tilstandsvariabel for grundvandsmagasinet at sammenkæde ændringer i grundvandsspejlet til pumpeprisen. Denne vandspejlsafhængige pris gjorde udtrykket for de samlede omkostninger ulineært og ikke-konvekst. Dette blev håndteret ved at kombinere en genetisk algoritme og lineær programmering. Udover regional grundvandssenkning blev også lokal grundvandssenkning, estimeret med Thiem's ligning, inkluderet. Dette muliggjorde analyse af det dynamiske samspil mellem overflade- og grundvand. Resultaterne viste, at grundvandsmagasinet fungerer som buffer i systemet og tillader overpumpning i tørre år til gengæld for øget opfyldning i regnfulde år. Dertil blev også den mest omkostningseffektive opfyldning af et overudnyttet grundvandsmagasin demonstreret.

Den tredje metode vurderede samspillet mellem vandressource- og vandkvalitetsforvaltning. Biokemisk iltforbrug (BOD) repræsenterede vandkvalitet i systemet, og allokering af vand blev tillagt generering af BOD samt en marginal pris for fjernelse af BOD. Begrænsninger på nedstrøms vandkvalitet blev rettet mod vandets iltindhold, estimeret med Streeter-Phelps ligningen. Ikke-lineære begrænsninger blev håndteret med hybriden af en genetisk algoritme og lineær programmering. Omkostningerne til at overholde de kinesiske vandkvalitetsstandarder var lave i forhold til omkostningerne til vandmangel fra det andet studie. Til gengæld blev den optimale fordeling af vandressourcerne meget påvirket, hvor tildelingen af ressourcerne blev skiftet mellem brugerne med henblik på bedre udnyttelse af vandet til fortynding.

De udviklede metoder blev med succes benyttet til at demonstrere, hvordan hydrologisk-økonomisk modellering kan lede til optimal vandresourceforvaltning i komplekse systemer. Metoderne er meget fleksible og kan anvendes i systemer, der kan afgrænses til maksimalt to reservoir-tilstandsvariabler. Beregningstiden reduceres betydeligt, hvis problemet kan holdes lineært og konvekst, men dette er ikke en forudsætning. Omkostningseffektiv forvaltning kan findes på tværs af traditionelt separate discipliner, og metoden repræsenterer dermed den type af integrerede løsninger, som er nødvendig for effektivt at imødekomme the 2011 No. 1 Central Policy Document.

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Abbreviations

BOD	Biochemical Oxygen Demand
CNY	Chinese Yuan (always in 2005 prices)
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
DP	Dynamic Programming
EFC	Expected Future Costs
FC	Future Costs
FCF	Future Cost Function
GA	Genetic Algorithm
IWRM	Integrated Water Resources Management
LP	Linear Programming
NCP	North China Plain
No. 1 Document	China 2011 No. 1 Central Policy Document
SDP	Stochastic Dynamic Programming
SNWTP	South-to-North Water Transfer Project
TC	Total Costs
WVT	Water Value Table
ZRB	Ziya River Basin

1 Introduction

Our natural resources and ecosystems are under increasing pressure by population growth and human activities (Steffen et al., 2007). The growing demand for water increases water scarcity and threatens ecosystems around the world. The North China Plain (NCP) is a 320,000 km² alluvial plain, formed by the Yellow, Huai and Hai rivers, that stretches across the Hebei, Henan, Beijing, Tianjin and Shandong provinces (Liu et al., 2011). Over the past decades, the area has been subject to increasing water scarcity as a consequence of rapid development, population growth and climatic variability (Liu et al., 2001, 2011; Liu and Xia, 2004). The plain is an economic hotspot with a population of 200 million people, a large industrial sector and extensive production of wheat and maize (Liu et al., 2011). The domestic, agriculture and industry sectors rely on access to clean water, and as water becomes more scarce, conflicts arise between the users. Water scarcity puts water resources and ecosystems under increasing pressure and complicates water management by forcing decision makers to prioritize water uses in a given system. Persistent overexploitation of the groundwater aquifer has caused declining groundwater tables and this, in combination with excessive storage of surface water for irrigation purposes, has implied that many rivers are running dry or becoming heavily polluted (Liu et al., 2001; Zheng et al., 2010).

As a response to the increasing water challenges, the China 2011 No. 1 Central Policy Document (No. 1 Document), a policy framework comparable to the European Water Framework Directive, has been released (Yu, 2011; Ministry of Water Resources, 2012; Griffiths et al., 2013b). While this policy document focuses mainly on targets related to different aspects of water scarcity and water quality, Yang et al. (2013) underline the need for an integrated approach to solve complicated and coupled water resources management problems. The targets in the No. 1 Document span across traditionally separate disciplines of water efficiency, water allocation and water quality management. While the targets can be set individually, solutions focusing on a single discipline might contradict solutions suggested by other disciplines. For example, river water quality is a result of pollution discharges and river flow. Thereby, acceptable pollution effluents cannot be determined without knowing, e.g., reservoir releases and water allocations. In this context, integrated water resources management (IWRM) promotes coordinated management of the resources, while ensuring economic and ecological sustainability and social equity (Loucks and van Beek, 2005).

Hydroeconomic analysis can be used to inform IWRM and provides a systematic and quantitative framework to evaluate the coupled hydrologic, engineering, environmental and economic activities in water resources systems (Harou et al., 2009). Competing water uses are represented using a common monetary unit. This converts complex multi-objective management problems into simple single-objective problems and allows assessment of economic trade-offs between the water uses (Harou et al., 2009). Hydroeconomic modeling has been used to solve water management challenges at different spatial scales, spanning from irrigation district to river basin scale and global scale.

Hydroeconomic studies typically address either pure water quantity allocation problems or pure water quality problems. Expansion of the model boundary, to couple water quantity problems with other aspects, such as water quality, has only been attempted in few studies (Karamouz et al., 2008). Increasingly effective algorithms and cheap access to computation power move the threshold for what is computationally feasible to include in hydroeconomic optimization models.

1.1 Research objectives

In this context, the PhD research was focused on the application of hydroeconomic optimization techniques to support integrated water resources management in northern China. The objectives of this PhD research were to:

- demonstrate how a hydroeconomic optimization approach can be used to support integrated water resources management (Paper I),
- develop a hydroeconomic optimization approach, which can guide management of coupled surface water and groundwater systems (Paper II),
- develop a hydroeconomic optimization approach for joint optimization of water quantity and water quality objectives (Paper III).

This synopsis summarizes the findings of the three research papers written as a part of the PhD study. In Chapter 2, the existing literature in the fields of hydroeconomics and reservoir operation is reviewed. The Chinese case study area is presented in Chapter 3, whereas Chapter 4 presents the methods used for this study. Chapter 5 provides an overview of the main results and Chapter 6 the main conclusions. Suggestions to future research directions are presented in Chapter 7. Following the synopsis, the papers are included in Chapter 9, in which also three field reports are inserted.

2 Hydroeconomic analysis

This chapter provides a literature review of the field of hydroeconomic modeling. The literature, however, also apply the terms *hydro-economic*, *hydro-logic-economic*, *economic engineering* and many others (Harou et al., 2009). This PhD study will apply the term *hydroeconomic*. A central input for the hydroeconomic models is the economic value of water, and this review presents an overview of valuation techniques and central challenges. As presented in the objectives, the PhD study focuses on deriving optimal water management for a river basin. Hydroeconomic optimization techniques, primarily within the field of reservoir operation, will thus be reviewed.

2.1 Planning and scheduling problems

Hydroeconomic models couple engineering, hydrology, environment and economics in a joint framework (Harou et al., 2009). A central concept of hydroeconomics is that the water demands in a system are not fixed requirements, as often the case in traditional engineering approaches, but are instead represented by value-sensitive water demand functions (Booker et al., 2012). Some or all water uses are valued using a joint, typically monetary, unit. This common framework allows decision makers to evaluate economic trade-offs and synergies between the water users.

Applications of hydroeconomic analysis are diverse and typically divided into planning and scheduling problems. In planning problems, hydroeconomic analysis is used to quantify economic impacts of alternative policies (Marques et al., 2006; George et al., 2011). The economic performance, with and without the new policies, is evaluated, and the best alternative, e.g., the lowest cost, is selected in a cost-benefit analysis. The planning problems can be new hydraulic infrastructure (e.g. reservoirs and canals), and institutional reforms, (e.g. water use efficiency and evapotranspiration management). One example is Marques et al. (2006), who used a hydroeconomic simulation approach to assess changes in user behavior and quantify economic and operational impacts as response to varying surface water costs and availability.

Hydroeconomic scheduling problems are solved to find the best possible water management of a system, given present infrastructure and management constraints. While the planning problems focus on “what if” scenarios, the scheduling problems find optimal operation rules for a given system. In these optimization-based approaches, the management problem is formulated as a constrained optimization problem, where decision variables determine an ob-

jective function, and the resulting optimal solution will typically satisfy an overall objective of minimizing costs or maximizing benefits (Pulido-Velázquez et al., 2006; Tilmant and Kelman, 2007). A hydroeconomic optimization reveals the shadow prices of water in the system. These shadow prices represent the true value of water and can be used to guide, e.g., water pricing (Pulido-Velazquez et al., 2013).

2.2 The economic value of water

The economic value of water used in the system is a central input to hydroeconomic analysis. In economic theory, users of a resource are classified as either producers or consumers (e.g. Griffin, 2006; Varian, 2010). Producers use inputs, one of them water, to create their products, and are maximizing their profit (Griffin, 2006). Similarly, consumers are trying to maximize their utility of consuming water and other goods, subject to a budget constraint. Typically, production functions show decreasing marginal profit (producers) and diminishing marginal utility (consumers) as allocation of water increases.

The water demand function (see Figure 1) shows the relationship between water price and the users' water demand (Griffin, 2006; Booker et al., 2012). In an ideal competitive water market, with complete information among the users, the users will adjust their demand for water until economic efficiency is obtained. At this point, the user's willingness to pay for the water is equal to the marginal utility or profit they get from the water. The area between the willingness to pay (demand function) and the supply function is defined as

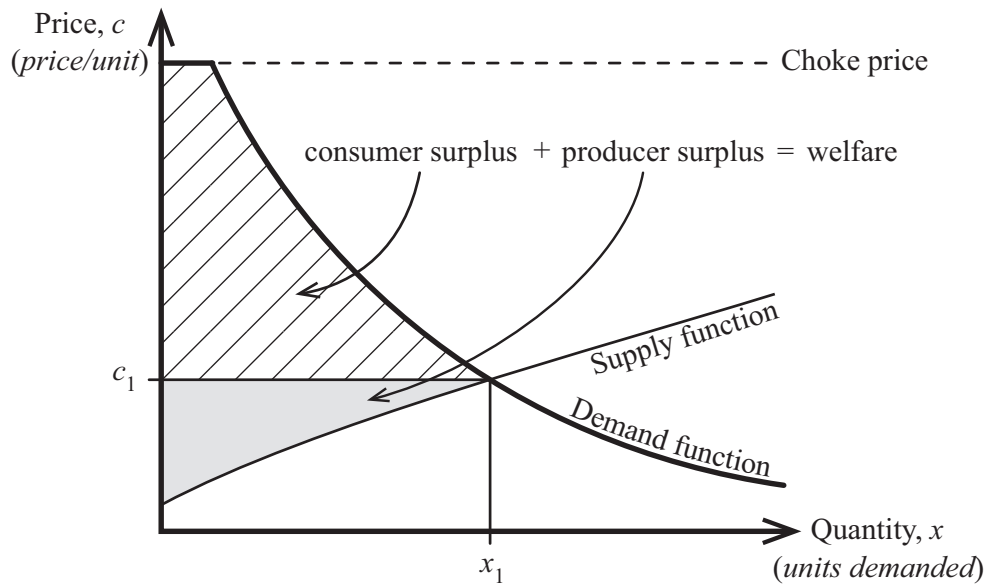


Figure 1: Water demand function modified from Harou et al. (2009). If the water price is equal to c_1 , the water demand will be x_1 .

consumer and producer surplus and are used as measures of welfare. The choke price marks the price where the consumers switch to an alternative source.

The producer's water demand function is often estimated using the residual imputation method (Scheierling et al., 2004; Ashfaq et al., 2005; Pulido-Velazquez et al., 2008; Riegels et al., 2013). This method assumes that all input costs, other than the cost of water, are known. The water value is then imputed as the residual of the observed gross benefits after all the non-water costs are subtracted (Young, 2005; Griffin, 2006). In short-term planning problems, a part of the costs may relate to sunk investments, which producers have no ability to shift. An example is irrigation planning in the middle of the crop growth cycle, where the costs of seeds and soil preparation are sunk.

Econometric approaches, a branch of applied microeconomics, are also commonly used in the literature to estimate the demand function (Arbués et al., 2003). Another method introduced by Howitt (1995), known as positive mathematical programming is commonly used to estimate the value of irrigation water (Cai and Wang, 2006; Riegels et al., 2013). In this approach, existing farming choices (land, irrigation) are assumed results of profit maximization, and used to parameterize the crop production function (Howitt, 1995).

Water demand functions of consumers are typically also estimated with econometric approaches (Arbués et al., 2003; Harou et al., 2009). A common simplification is known as the point expansion method (Gibbs, 1978; Dalhuisen et al., 2001; Arbués et al., 2003; Jenkins, 2003; Griffin, 2006). An observed water price and water use are assumed to represent a point on the demand function, and an assumed user-dependant price elasticity is used to generate the full demand function (e.g. Griffin, 2006). A main challenge when estimating the price elasticity (percent change in demand per percent change in price) is the level of aggregation of the users, as the price elasticity reflects, e.g., the user's budget.

Market failures are common problems associated with the introduction of water markets (Young, 2005; Harou et al., 2009). *Public goods*, such as environmental protection, and *externalities*, such as water quality, are examples of market failures, where the free market fails to be efficient (e.g. Griffin, 2006). Here, a water user has no economic reason for paying to protect the interest of another water user. Another critical problem is that water users *over-discount* the future value of water (Griffin, 2006). An example is over-exploitation of groundwater resources, leading to increased future costs.

The hydroeconomic literature provides different solutions how to correct or reduce market failures. While often considered controversial, valuation of ecosystem services have widely been attempted (e.g. de Groot et al., 2002, 2010; Fisher et al., 2009). Also constraints, such as minimum in-stream flows for ecosystems, are commonly used alternatives to including the ecosystem value in the hydroeconomic analysis (e.g. Pulido-Velázquez et al., 2006; Medellín-Azuara et al., 2009). The optimized water management will thereby better represent the interest of society. Water taxation and compensation are suggested as regulative tools for the decision makers, to reallocate water resources and approach societal optimum (Harou and Lund, 2008; Tilmant et al., 2009).

2.3 Hydroeconomic optimization

In operations research, choices available to decision makers are represented as decision variables, which are linked to performance measures (e.g. Hillier and Lieberman, 2001). In the context of hydroeconomic modeling, this performance measure is expressed in monetary units. Any rules or requirements to the decisions, e.g., water balance, reservoir storage capacity or water demands, are included as constraints. These constraints are formulated as, often linear, mathematical expressions. In an optimization model, the search algorithm is used to identify the decision variables, which satisfy an overall objective of either minimizing or maximizing the objective value, while complying with the constraints (Hillier and Lieberman, 2001).

Hydroeconomic optimization models are commonly used to find the optimal distribution a finite amount of water between the water users. Typical water sources include surface water, groundwater, desalinated water and water transferred from other basins (Cai and Wang, 2006; Pulido-Velázquez et al., 2006; Karamouz et al., 2010). Hydroeconomic optimization models are used to trade-off water allocations both spatially and temporally between the users. Simple linear spatial allocation problems are usually solved with linear programming (LP, see e.g. Loucks and van Beek, 2005). Presence of, e.g., a reservoir enables temporal storage of water, which increases the decision space and requires more advanced optimization approaches.

Storage (surface water reservoirs and groundwater aquifers (surface water reservoirs and groundwater aquifers, e.g. Pulido-Velázquez et al., 2006), water pollution (Cardwell and Ellis, 1993) and delayed yield in agriculture (Tilmant et al., 2008) are examples of dynamic management problems in water management. With an objective to, e.g., minimize scarcity costs over a

planning period, the decision of releasing water in time t affects the water availability and hence the feasible decision space in time $t+1$ (see Figure 2). The decisions are thereby coupled in time, and the optimal solution will consist of a series of reservoir releases, which together satisfy the overall objective.

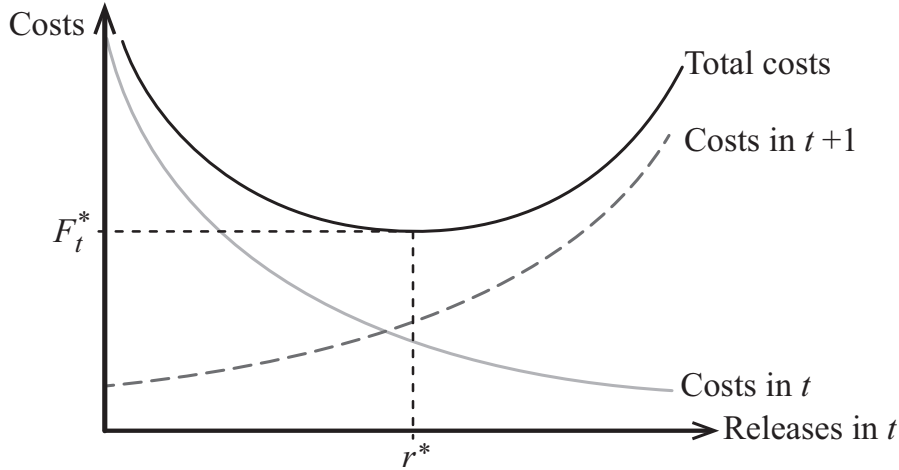


Figure 2: Minimization of total costs in DP. Increasing reservoir releases in t reduces the immediate costs in t , but also increases the future costs. The optimal reservoir release r^* , minimizes the total costs and yields the optimal objective value, F_t^* .

Dynamic programming (DP) is a popular optimization framework for solving optimization problems with sequences of interrelated decisions (Hillier and Lieberman, 2001; Loucks and van Beek, 2005). In DP, the original optimization problem is divided into a set of smaller linear or non-linear optimization problems, which are solved individually (Loucks and van Beek, 2005). A problem of DP is that all the discrete sub-problems (e.g. for all discrete reservoir storage volumes) must be solved, before the optimal policy through time can be found. An increasing number of discrete state variables result in exponential growth in the number of sub-problems to solve, hence also the computation time. This principle is known as the *curse of dimensionality* (e.g. Hillier and Lieberman, 2001).

Stochastic dynamic programming (SDP) is based on DP, but allows for a more realistic representation of uncertainty in the input data (e.g. Stedinger et al., 1984; Labadie, 2004; Loucks and van Beek, 2005). In the SDP framework, the objective function finds the optimal present and expected recursively calculated future costs or benefits (e.g. Pereira and Pinto, 1991; Tilmant et al., 2008). Stochasticity, typically in the reservoir inflow, is represented as

additional discrete state vector. Despite the application of SDP being limited to three or four state variables, it has been widely applied in the literature (e.g. Labadie, 2004; Tilmant et al., 2008; Pereira-Cardenal et al., 2014). Stage and Larsson (1961) presented the water value method, an application of SDP, which determines and stores the shadow prices for all state combinations (e.g. Wolfgang et al., 2009).

Stochastic dual dynamic programming (SDDP, Pereira and Pinto, 1991) is an extension of the SDP framework. Instead of mapping the entire decision space, SDDP overcomes the curse of dimensionality by sampling iteratively around the optimal solution until convergence is achieved. The expected cost-or benefit-to-go functions are approximated with linear functions. This approximation uses Benders cuts, which requires a convex future benefit or cost function (Pereira and Pinto, 1991). SDDP has been used in the literature to solve multi-dimensional, optimization problems (e.g. Tilmant et al., 2009, 2012; Goor et al., 2011).

Heuristic programming is a group of search techniques, including evolutionary algorithms, which use rules-of-thumb or experience to find the approximate global optimal solutions (Hillier and Lieberman, 2001; Labadie, 2004). Genetic algorithms (GA) search for optimum through an imitation of natural evolution and are widely used in water management (Reeves, 1997; Nicklow et al., 2010). Despite computationally expensive, a GA is a robust tool to find the approximate optimum of complex non-linear and non-convex problems (Labadie, 2004).

Cai et al. (2001) presented hybrid implementation of GA and LP. The GA optimizes over a low number of complicating variables, which, when fixed, turns the remaining optimization problem into an LP. This reduces the computation time and allows for application in large-scale non-linear water management problems (Cai et al., 2001; Labadie, 2004; Cai and Wang, 2006).

Hydroeconomic models have commonly been targeting pure water quantity management problems (e.g. Pulido-Velázquez et al., 2006; Heinz et al., 2007; Tilmant et al., 2012) or pure water quality management problems (e.g. Cools et al., 2011; Hasler et al., 2014). Water quantity and water quality are, however, strongly coupled elements in water management and should ideally be integrated in a joint modeling and optimization framework. Despite of this coupling, only few studies have addressed optimization of coupled water quantity-quality problems. Cai et al. (2003) used a simple decomposition approach to maximize the sum of irrigation, hydropower and ecological benefit

subject to salinity control in a complex multi-reservoir basin. Kerachian and Karamouz (2007) developed a GA-based optimization approach to resolve water conflicts from water demands, water quality and waste load allocations. Ahmadi et al. (2012) introduced a GA-based multi-objective approach to guide quality and quantity management, while maximizing upstream agricultural production.

3 Case study: The Ziya River Basin

The Ziya River Basin (ZRB) is subject to severe water scarcity, the water management problem is complex with multiple water sources, water users and reservoirs and there are multiple conflicting economic activities. The basin is therefore a good case to demonstrate hydroeconomic analysis. This chapter will provide an overview of the hydrological system, the water conflicts and the institutional setup in the ZRB.

3.1 Hydrological system

The Ziya River runs in a medium-sized river basin located on the North China Plain between the Yellow and Hai Rivers. The rivers drain about 52,000 km², where the average precipitation is approximately 500 mm/year and runoff from the upstream mountains is 3 km³/year (Paper I). The basin has two major tributaries, the Hutuo River and the Fuyang River. Hutuo River is formed by mountain tributaries in the eastern Shanxi Province before it crosses the Taihang Mountains and the Hebei Province on its way to the Gulf of Bohai as presented in Figure 3. Fuyang River is formed by confluence of a number of smaller rivers from the Taihang Mountains. Naturally, the two rivers were separate tributaries to the Hai River.

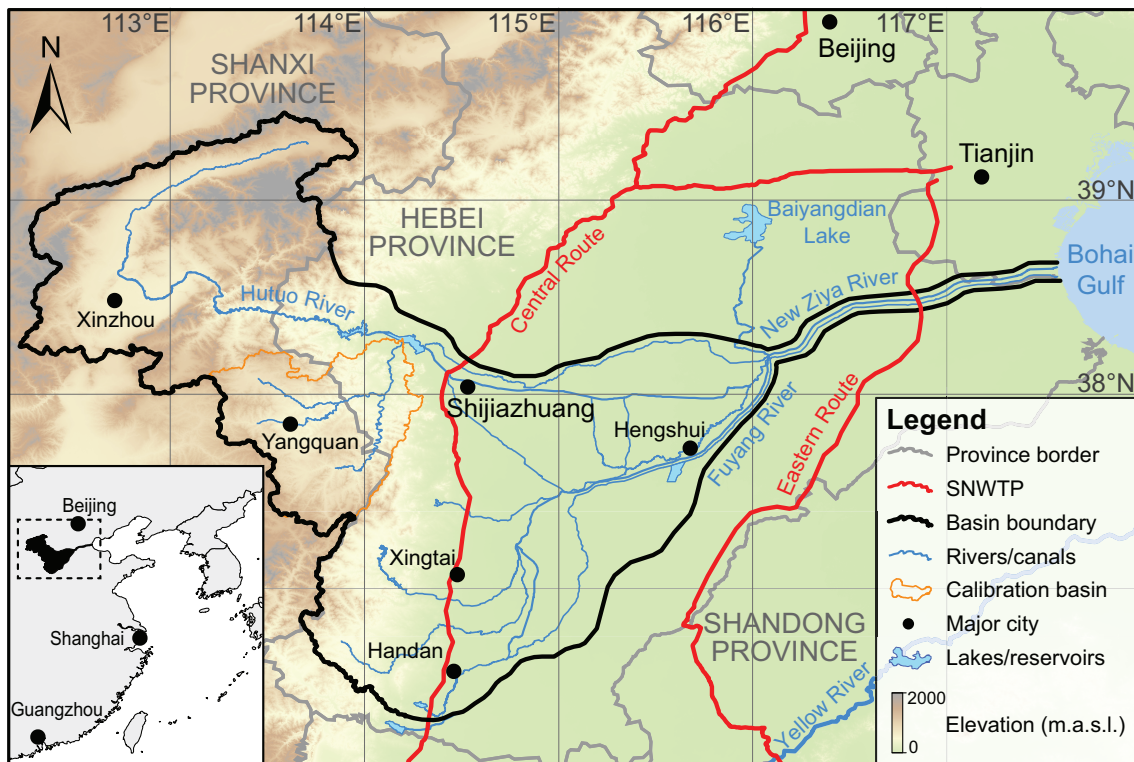


Figure 3: The Ziya River Basin, China, based on Paper I.

As a part of the flood control initiatives, the rivers have been joined and diverted to the Gulf of Bohai through a wide spillway named New Ziya River. The field reports (IV-VI) present a number of photos from the basin.

3.1.1 Hydropower reservoirs

A number of reservoirs are located in the ZRB. Most are minor private reservoirs in the mountains, which are used to supply small villages with drinking and irrigation water. Two major reservoirs, Gangnan (see Figure 5) and Huangbizhuang, are located on the Hutuo River close to Shijiazhuang, the provincial capital of the Hebei Province. The combined reservoir storage capacity of 2.78 km^3 (HWCC, 2012) is more than the average yearly runoff from the Hutuo River. An overview of the major hydraulic infrastructure in the basin is presented in Figure 4.

The three reservoirs Lincheng, Zhuzhuang and Dongwushi are all located in the Fuyang River sub-basin at the border between the Taihang Mountains and the NCP. Another reservoir, Yuecheng, is located outside the catchment, but delivers drinking water to the city of Handan through an underground pipe. Further, a canal connects the reservoir to the Fu Dongpai River, which is connected to the Fuyang River, as verified in field report IV.

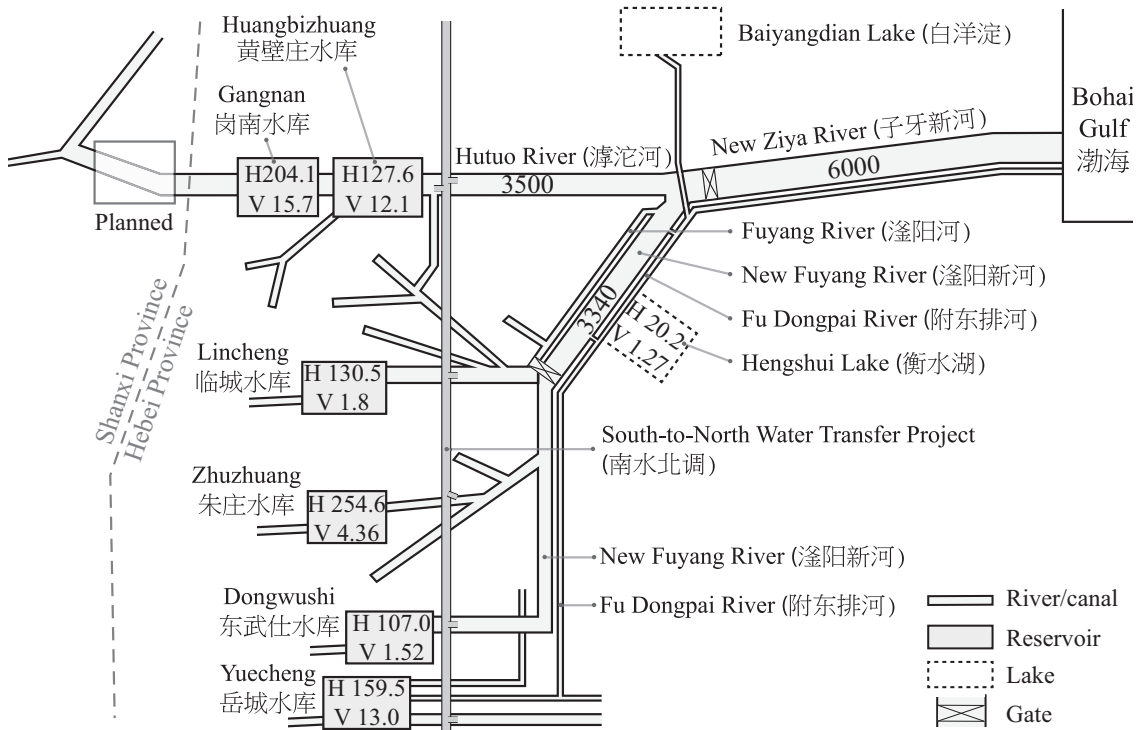


Figure 4: Conceptual sketch of the Ziya River Basin modified from HWCC (2012) and updated with field observations, where H is the maximum head (m.a.s.l.) and V is the storage volume in 10^8 m^3 . The flow capacities (m^3/s) of the main spillways are indicated.

Flood control is the main role of reservoirs, but hydropower turbines are installed in all the reservoirs. In Paper I, the capacity was estimated to 66 MW with a turbine capacity of 1.5 km³/month. The average marginal hydropower benefit was estimated to 0.036 CNY/m³ (CNY = Chinese Yuan in 2005 prices), but varies between the reservoirs due to different hydraulic heads and turbines.

Minor reservoirs are located in the mountains and in the upper Hutuo basin in the Shanxi Province. While most are insignificant seen from a system perspective, a few medium-sized reservoirs are sufficiently large to affect the water balance notably. One example is the Xiaruyue Reservoir, which cuts the upper 50 km of the Hutuo River as presented in field report IV. The present management of these reservoirs, where only small portions of irrigation water are released, is expected to highly affect the water availability to downstream users.

3.1.2 Rainfall-runoff model

A central element in the context of water management is water availability. The daily discharge in the main rivers has been monitored daily for more than 50 years by the Chinese authorities (MWR. Bureau of Hydrology, 2011). Because of a high level of water abstraction from the rivers, the measured discharge is, however, not representative for the actual runoff. Limited data availability prevents the use of abstraction data to correct the measured discharge. Further, the discharge stations are typically located downstream the reservoirs, thereby reflecting the reservoir management rather than the runoff. Instead, the natural runoff was estimated with the rainfall-runoff model presented in Paper I. The model is based on the Budyko framework (Budyko, 1958; Zhang et al., 2008), and uses Hargreaves method to estimate daily evapotranspiration from daily maximum and minimum temperature. Measured precipitation and temperature were available from 6 weather stations in the area (China Meteorological Administration, 2009).



Figure 5: The Gangnan Reservoir in June 2012.

The volume available for allocation was assumed equal to the natural runoff from six sub-basins upstream of the reservoirs as presented in Paper 1. The resulting runoff is presented in Figure 6. Runoff from the NCP downstream of the reservoirs was not included in this study. This assumption can be justified by the limited surface runoff, a result of the flat plain and a high infiltration capacity. Further, the downstream runoff cannot be stored and is therefore of low value in the rainy season where the irrigation demands are low (rainfed crops).

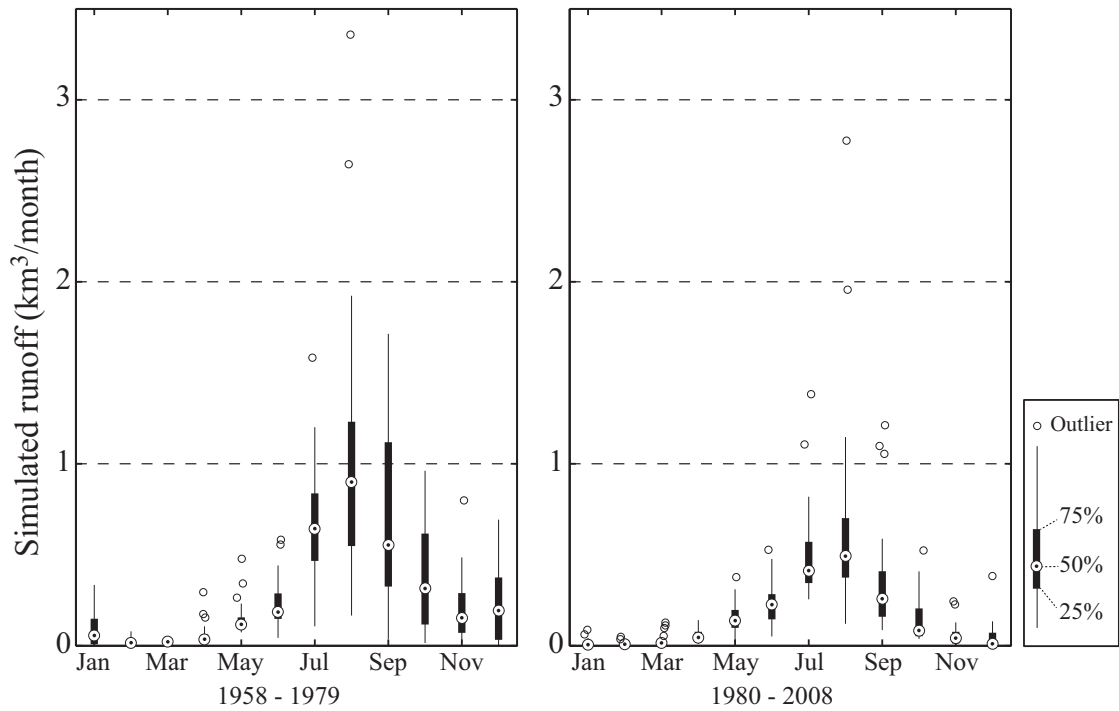


Figure 6: Simulated runoff from seven sub-basins upstream reservoirs for 1958-1979 and 1980-2008 with 25%, 50% and 75% quantiles indicated. The lengths of vertical lines are up to 3/2 of the black boxes.

A single sub-basin for a tributary to the Hutuo River (see Figure 3) was used for auto-calibration, which maximized the Nash-Sutcliffe efficiency. Data availability and highly modified runoff prevented calibration to runoff from other sub-basins. The discharge from the tributary was assumed close to natural, given a low population density and absence of major reservoirs. However, minor reservoirs and weirs were observed on the field trips and despite a low population density relative to the area, the city Yangquan with 1.4 million inhabitants is located in the sub-basin (Shanxi Statistical Information Network, 2011). The calibration results and the simulated runoff are presented in Paper I (Fig. 3).

While the performance of the rainfall-runoff model is not optimal, this project focused primarily on the water management, and the performance of the hydrological model was considered sufficient for demonstration purposes. Over the past decades, the region has experienced a reduction in the annual precipitation. This change is seen in the precipitation measurements (China Meteorological Administration, 2009) and has been discussed in the literature (see Paper I and III). The regional precipitation change is clearly reflected in the simulated runoff as presented in Figure 6.

3.1.3 South-to-North Water Transfer Project

The South-to-North Water Transfer Project (SNWTP) consists of three large hydraulic infrastructure projects to divert water from southern China to the dry north in open channels. The western and shortest route diverts water from the upper tributaries of the Yangtze River to the upper Yellow River. The Eastern route diverts water from the lower Yangtze River and through the 1150 km long Grand Canal to Tianjin. The central (or middle) route will annually divert 9.5 km³ water (water-technology.net, 2013) from a tributary of the Yangtze River to 100 cities in northern China (Wang and Ma, 1999). This 1230 km long canal crosses the ZRB downstream the reservoirs (see Figure 3 and 4).

In 2008, the first part of the central route, from Shijiazhuang to Beijing, was completed (see Figure 7). In Shijiazhuang, the SNWTP is connected to the Gangnan and Huangbizhuang Reservoirs, allowing diversion of Ziya River water to Beijing. In 2014, the remaining part of the central route was completed. Besides Gangnan and Huangbizhuang Reservoirs, Yukuai and Xidayang Reservoirs north of the ZRB can be diverted to the central route (Liang, 2006) as well. Further, water can be diverted from the central route to a number of intersecting rivers. In the ZRB, at least 14 such diversion points can be observed in satellite images (Google Inc., 2013).



Figure 7: The central South-to-North Water Transfer Project route at Baoding, June 2012.

3.2 Water challenges

The ZRB faces a number of serious water challenges. Most important is extreme water scarcity, which forces the water managers to prioritize between conflicting water uses. Further, the remaining surface water is highly polluted, which leads to additional conflicts between users. The last major challenge is the high water resources utilization, which causes dry rivers and threatens the natural ecosystems.

3.2.1 Water demands and water scarcity

The ZRB is home to 25 million people (Bright et al., 2008), of which 19 million (730 people/km²) are located on the NCP in the downstream basin. As illustrated by the satellite images in Figure 8, the area is covered by a large number of small villages in the farmland. According to the National Bureau of Statistics of China (2011), the domestic users in the Hebei Provinces consume on average 123 L/person/day, while the users in the Shanxi Province consumes 106 L/person/day.

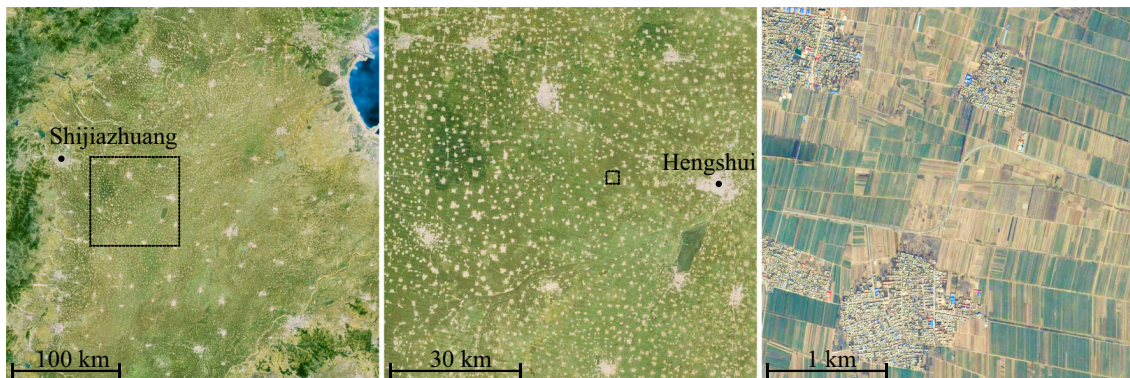


Figure 8: Satellite images of the NCP at 3 different scales (Google Inc., 2013). The boxes indicate coverage of the next image.

The agricultural sector consists of mainly small family farms with users having access to approximately 1 mu (1/15 hectare) of land per person in the household (see field reports **IV-VI**). The small plots of farmland are cultivated using manual labor and small tractors. Most of the NCP farmers use a double-cropping system with winter wheat grown during the dry season in the spring (March-May) and maize grown in the rainy season during the summer (June-September). The winter wheat is therefore highly dependent on irrigation water, while the maize is mainly rain fed. In the upper basin, the growing season is shorter than on the NCP due to higher elevation. Here, the farmers are limited to a single crop and typically grow maize. The typical irrigation schedule is shown in Paper **I** (Table 2). In contrast to the

agriculture, the industrial sector is diverse and spans across heavy industries (e.g. chemicals and petroleum), mining (e.g. coal and steel) and food production.

The water demands are summarized in Table 1. In the area upstream reservoirs, the water demands are mainly satisfied with groundwater and surface water, while water users downstream the reservoirs recently also receive SNWTP water. The rural villages in the downstream basin typically pump groundwater from the deep aquifer (>200 m below surface), as the surface water is polluted. The farmers close to rivers typically rely on the polluted river water, while farmers far from the rivers pump groundwater.

Table 1: Annual water demands and water availability in the ZRB, adopted from Paper I.

	Water (km³/year)
Water demand	
<i>Domestic</i>	1.1
<i>Industry</i>	1.1
<i>Irrigation, maize</i>	2.1
<i>Irrigation, wheat</i>	6.1
<i>Beijing</i>	1.0
Total	11.3
Water availability	
<i>Renewable groundwater</i>	2.3
<i>Surface runoff</i>	2.9
<i>SNWTP water</i>	1.3
Total	6.5

The surface water availability is estimated to 2.9 km³/year with the rainfall-runoff model. The groundwater availability is estimated to 17.5% of the precipitation (Wang et al., 2008) equal to 2.3 km³/year. Finally, the SNWTP water available to Beijing and the ZRB users are in Paper I estimated to be 1.3 km³/year. This brings the total water availability to 6.5 km³/year and results in an annual water balance deficit of 4.85 km³/year. A large part of this water deficit has in the past been covered by overexploitation of the groundwater aquifer, causing the groundwater table to decline with more than 1 m/year (Liu et al., 2001).

3.2.2 Water pollution

Another major challenge in the ZRB is water quality. Wastewater treatment capacity has not followed the population growth and economic development, and most of the rivers on the NCP are today heavily polluted. Most of the rural areas have limited or no access to wastewater treatment, and the rivers on the NCP share characteristics with untreated wastewater. The major pollutants include chemical oxygen demand (COD), biochemical oxygen demand (BOD) and ammonia (Ministry of Environmental Protection, 2010). In addition, chemicals from the industries are also major challenges.

As presented in Paper **III**, the Chinese authorities operate with 5 water quality standards with grade I representing clean natural water and grade V considered heavily polluted (HRB WRPB, 2008). According to the Ministry of Environmental Protection (2010), 42% of the river stretches in the Hai River Basin failed to meet the Grade V standard in 2009. While significantly cleaner than the NCP rivers, anaerobic sediment and some degree of water pollution were observed in the upper Hutuo River (see field report **IV**).

3.2.3 Wetlands and ecosystems

Lake Baiyangdian, the largest natural lake in northern China, is located 65 km north of the Ziya River. The lake is classified as class AAAAA (highest level) tourist attraction by China National Tourism Administration (2008). The high level of abstractions from the rivers and the reduced natural runoff has reduced the natural inflow to the lake (Liu et al., 2006). As a result, the water level has declined, greatly reducing the quality of the ecosystem (Liu et al., 2006). During a drought in 2006, decision makers decided to allocate water to the lake, despite the farmers and domestic users were also suffering from water scarcity (Honge, 2006).

Construction of a permanent connection from the Yuecheng Reservoir to the Baiyangdian Lake was announced in 2004 (China Daily, 2004). The Fu Dongpai River (see Figure 4) will bring water to the confluence point of Hutuo and Fuyang Rivers. The field trips showed that water can be moved between the Fuyang, New Fuyang and Fu Dongpai Rivers at multiple points upstream the confluence point and north to the Baiyangdian Lake (see field report **V** and **VI**). The annual water deficit in the lake is more than 100 million m³ (Honge, 2006).

Another large lake, the artificial Hengshui Lake south of the city Hengshui, has also experienced decreasing water levels after it was separated from the

Fuyang River due to insufficient water quality. A canal from the Yellow River is today used to divert water to the lake (see field report IV and V) (Hengshui City Water Authority, 2011).

The rivers and irrigation canals are with few exceptions heavily polluted or dry and thereby without any value to the ecosystems. An exception is the old Hutuo River in the Taihang Mountains, which has small wetlands and stretches with turbulent flow (see field report IV).

3.3 Institutional setup

The Chinese institutional and regulatory setup in the context of management of water resources is complex. A large number of governmental, provincial and river basin agencies are involved, and this chapter provides a brief overview of the present situation.

In China, a total of 9 central water administration agencies are involved in the water resources management decision making (after Feng et al., 2006):

- The *Ministry of Water Resources* manages the water quantities of both the surface water and groundwater resources and is in charge of overall planning and coordination of flood control along with coordinating a unified water resources administration.
- The *Ministry of Environmental Protection* deals with water quality and manages the national water quality and pollutant discharge standards.
- The *National Development and Reform Commission* coordinate planning of water resources development and ecosystem building.
- The *Ministry of Housing and Urban-Rural Development* deals with the domestic sector and plans, constructs and manages water supply systems and waste water disposal.
- The *Ministry of Agriculture* is in charge of construction and management of irrigation infrastructure, non-point source pollution control and protection of the aquatic environment.
- The *State Forest Bureau* protects forests and watershed ecology.
- The *State Electric Power Company* constructs and manages large and medium size hydro-power projects.
- The *Ministry of Transportation and Communications* manages pollution control in relation to navigation on rivers.
- The *Ministry of Health* manages the drinking water standards.

Besides the central agencies, seven river basin commissions, one for each major river basin in China, manages the water resources. The river basin commissions are coordinated by the Ministry of Water Resources and have the responsibility of allocating the water resources to the administrative regions and sub-regions at basin level (Shen and Speed, 2009). The ZRB is administrated by the Hai River Water Conservancy Commission in Tianjin, which was visited as a part of the field trip in June 2012 (field report **IV**).

At province scale, provincial water managers use a water permit system to divide the water between major uses, such as supply companies and irrigation district managers (Shen and Speed, 2009). Each granted permit is eventually divided between the end-users by the major users (Shen and Speed, 2009). The irrigation end-users are notified about reservoir scheduled releases ahead of the cropping season (field report **VI**). A series of local irrigation managers diverts the irrigation water from the main rivers to irrigation canals, from which the farmers can pump their share of water to their fields.

Particularly the roles of the ministries of Water Resources and Environmental Protection overlap (Feng et al., 2006; Griffiths et al., 2013a). As an example, both have the responsibility of regulating pollutant discharges to the rivers. Further, the present legislation forces the river basin commissions to share authority and responsibility with provincial water managers (Griffiths et al., 2013a). Griffiths et al. (2013) conclude that the legislation makes it nearly impossible for the river commissions to enforce systems of total abstraction quantity control. Authority on abstraction charges and other central elements for an opportunity cost pricing (OCP) scheme are also beyond the power of the river basin commissions. The present Chinese institutional setup in the context of water resources management is therefore not an ideal setting for hydroeconomic studies like the ones proposed in this thesis. However, the China No. 1 Central Document of 2011 (No. 1 Document) described in Paper **III** provides a strong indication of willingness in the Chinese Government to push the Chinese water sector into a sustainable direction.

3.4 Formalization of management problem

This PhD study targets the water management problem faced by the river commission. At this high administrative level, the objective is to distribute the scarce water resources between the provinces as sketched in Figure 9. Runoff from the mountains can be allocated to the users in Shanxi or flow into the reservoirs. From here, water can be released to the users in the Hebei province or be diverted to Beijing. Unused water flows to the Bohai Gulf or the Baiyangdian Lake. Besides surface water, the users have access to groundwater and SNWTP water.

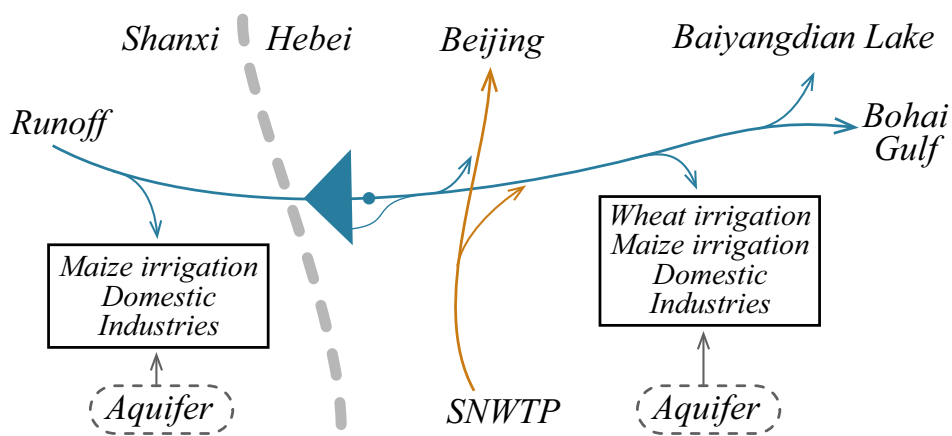


Figure 9: Sketch of the simplified management problem

The downstream rivers are highly connected by irrigation canals (field report IV) and surface water can be diverted from any reservoir to a large part of the downstream water users. Therefore, it is a reasonable assumption to aggregate the surface water reservoirs into a single central reservoir.

4 Methods

The previous chapter provides an overview of the complex water management problem of the ZRB. In this chapter, a framework to guide management of water resources based on the hydroeconomic concepts from Chapter 2 is proposed. In this PhD study, the water resources management is formulated as a hydroeconomic optimization problem, with the objective to minimize the total societal costs arising from water management and water scarcity in the ZRB. Chapter 4.1 presents the general optimization techniques, while Chapter 4.2 shows the application to the ZRB case. Finally, Chapter 0 demonstrates application of the results in decision support.

4.1 Optimization techniques

The management problem in Chapter 3 includes a set of quantifiable allocation decisions to be made by the decision makers. Water availability is estimated with the rainfall-runoff model presented in Chapter 3.1.2 and represented as a stochastic input to the optimization. Water users are characterized by their water demands and curtailment costs. The curtailment costs are defined as the marginal cost of not meeting a user's water demand, and the sum of all water curtailments is the total water scarcity costs. The total societal costs are the sum of the scarcity costs, the supply costs and any other costs and benefits associated with the water management, e.g. water treatment costs and hydropower benefits. The water users have access to surface water, groundwater and SNWTP water as described in Chapter 3.

4.1.1 Dynamic Programming

Loucks and van Beek (2005) and Hillier and Lieberman (2001) provide detailed introductions to the DP framework and application in reservoir operation and water management. Consider the simple optimization problem sketched in Figure 10 with three users and a reservoir. Initially, the reservoir storage state variable is discretized, i.e. divided into smaller volumes.

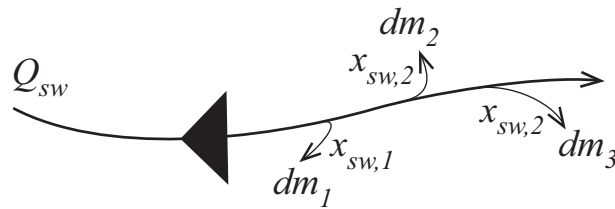


Figure 10: Simple dynamic management problem with reservoir inflow (Q), three users with water demands (dm), and water allocation decision variables (x_{sw}).

In Figure 11, three discrete reservoir storage volumes are shown for four time steps (stages). In a backward recursive optimization, t is the starting point. For each state, a sub-problem to minimize the immediate costs (IC) is solved:

$$F_t^*(V_{sw,t}, Q_{sw,t}) = \min(IC(V_{sw,t}, Q_{sw,t})) \quad (1)$$

where F_t^* is the optimal objective value in t (e.g. CNY), sw is surface water, V is the discrete reservoir storage state (e.g. m^3), and $Q_{sw,t}$ is the reservoir inflow in time t (e.g. m^3/month).

The immediate costs can for example be formulated as the cost of not meeting the user's water demand:

$$IC_m = (dm_m - x_{sw,m})c_{ct,m} \quad (2)$$

where m indexes the users, dm is the user's water demand (e.g. m^3), and $c_{ct,m}$ is the curtailment cost, i.e. the marginal cost of not meeting the water demand (e.g. CNY/ m^3).

In Figure 11, a conceptual sketch of discrete DP is presented. For each discrete state in t , the minimum immediate costs-to-go to the end of the planning period, along all possible pathways to the discrete storages in $t+1$, are computed. The arrows in Figure 11 show all the feasible pathways along with fictive values. The optimal path (bold arrows) is the decision resulting in the minimum total costs, i.e. sum of immediate and future costs. After repeating this for all the discrete states in t , the optimization moves one stage backward in time and tests again all possible state transitions for each discrete state.

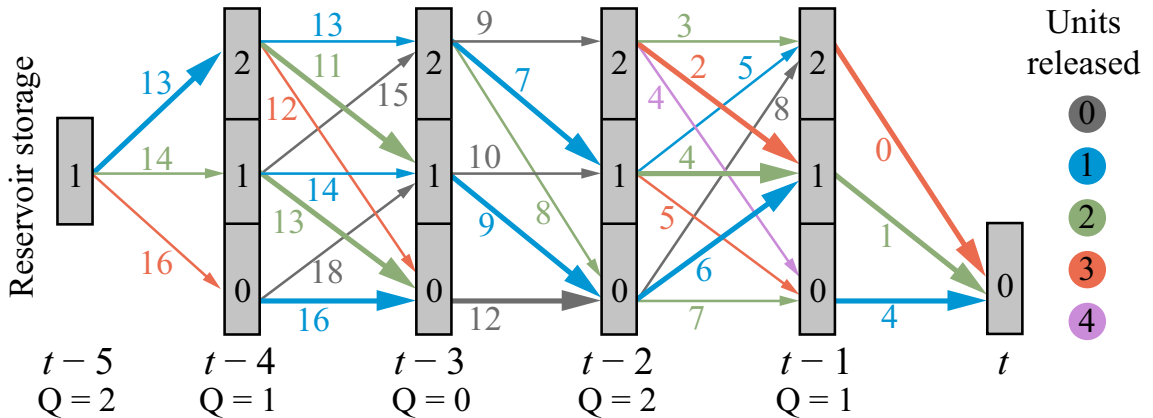


Figure 11: Conceptual sketch of discrete DP, where the arrows indicate feasible pathways, arrow colors the units of water released, the bold arrows show the optimal decision and the numbers indicate the total costs until the end of the planning period.

The optimization terminates after the state transition costs have been found for all discrete states and stages. From any discrete initial storage, the optimal management can now be extracted as the least-cost pathway to the end of the planning period. In Figure 11, the minimum total cost from an initial storage of one unit in $t-5$ is 13 (pathway: one-to-two, two-to-one, one-to-zero, zero-to-one and one-to-zero storage). In this example, the reservoir storage is low, relative to inflow and the demands. When applied in large scale, a fine discretization is needed to avoid the model spilling water or unnecessarily curtailing users, in order to fit with the discrete end storages. This fine discretization comes at high computational costs.

4.1.2 The water value method

The water value method (Stage and Larsson, 1961), an alternative to the discrete DP, is presented in Figure 12. Instead of fully discrete initial and end states, the water value method uses free end storage by approximating the future costs with linear functions using Benders cuts. For each discrete reservoir state, the sum of the IC and the future costs (FC) is minimized:

$$F_t^*(V_{SW,t}, Q_{SW,t}) = \min(IC(V_{SW,t}, Q_{SW,t}) + FC(V_{SW,t+1}, Q_{SW,t+1})) \quad (3)$$

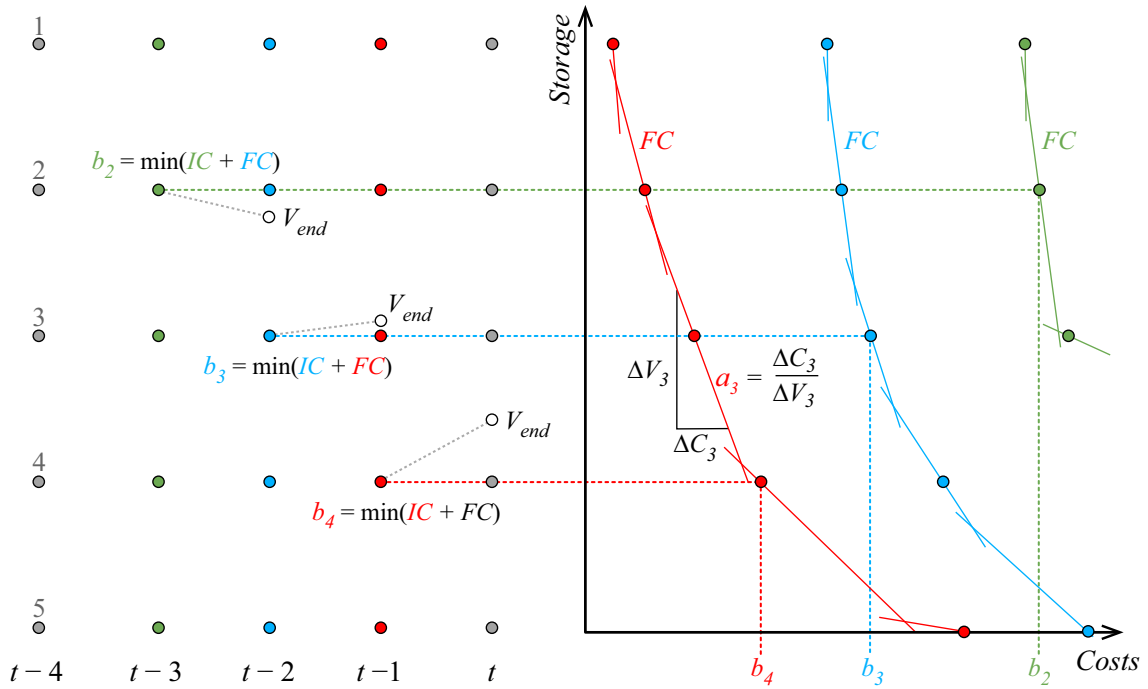


Figure 12: Generation of the future cost functions in backward recursive dynamic programming, using the water value method (Stage and Larsson, 1961). The discrete reservoir states (1-5) are indicated for different five different stages (t to $t-4$).

Table 2: A three-state discrete Markov chain with transition probabilities p_{kl} from state k in t to state l in $t+1$. The states 1, 2 and 3 represents, e.g., *wet*, *normal* and *dry* flow classes.

		$t + 1$		
		1	2	3
t	1	p_{11}	p_{12}	p_{13}
	2	p_{21}	p_{22}	p_{23}
	3	p_{31}	p_{32}	p_{33}

The minimum total costs and the value of the last unit water allocated to the users (shadow price) are stored for each sub-problem. As the optimization moves one stage backward in time, these are used to create a piecewise linear future cost function (FCF). At the initial stage t , the FC are assumed zero, i.e. no costs are associated with management from $t+1$ and forward. At stage $t-2$, the results stored in $t-1$ are used to generate the FCF, illustrated by the red line in Figure 12. The FCF consists of five line segments, each defined by a point (the minimum total cost) and a slope α (the shadow price). The FC and future storage can be selected as any point larger than or equal to the line formed by the line segments. If convex, all the linear segments will be binding in a part of the FCF. When the minimum total costs for all discrete states in $t-2$ are found, the optimization move one stage backward. Now the stored results from $t-2$ are used to generate a new future cost function (blue line). The optimization terminates after the minimum total costs have been found for all discrete states and stages.

By allowing free future storage, the number of discrete states can be reduced without introducing significant discretization errors. Another difference is that the management is not interconnected if there is free future storage, i.e. the optimal future reservoir storage found in $t-3$ was not optimized in $t-2$. A forward-moving post-processing simulation is therefore needed to find the consecutive management.

The forward-moving simulation can be initiated from any given reservoir storage and (3) is used to minimize the sum of the immediate management and the future costs of moving one stage ahead. The results stored in the backward optimization, are used to generate the future cost function. The optimal solution again output the optimal future storage, and the simulation can move one step ahead with this storage as initial condition.

4.1.3 Representation of uncertainty

The future water availability is uncertain and is included in the optimization framework as a stochastic variable. The simulated historic runoff contains valuable statistical information about the serial correlation. This transition probability can be represented as a discrete Markov chain (Table 2).

Stationary climate is a central assumption for the Markov chain approach. As documented in Chapter 3.1.2, this is, however, not the case in the ZRB, where a regional climate change has caused a drop in the water availability. As presented in Paper I, this study splits the 51 years into two assumed stationary climate periods with 1980 marking the year of transition. The runoff time series is split into the two climate periods, the shortest being 22 years long. Three flow classes are selected as a fitting size of the Markov chain.

The simulated runoff is first normalized and aggregated to monthly time steps. Each month is classified into the three flow classes, defined as *dry* (0-20th percentile), *normal* (20th-80th percentile) and *wet* (80th-100th percentile). The transition probabilities p_{kl} are found by counting the number of transitions from inflow class k in month t to inflow class k in month $t+1$. The resulting transition probabilities are used to represent the stochastic characteristics of the runoff. The Markov Chain is validated to ensure second-order stationarity (Loucks and van Beek, 2005) as described in Paper I.

4.1.4 Stochastic dynamic programming

In SDP, an additional discrete state vector to represent stochasticity, typically of the reservoir inflow, is introduced. In each stage, reservoir state and runoff flow class, the optimal management is found as the sum of the IC and expected future costs (EFC) as shown in the Bellman formulation:

$$F_t^*(V_{sw,t}, Q_{sw,t}^k) = \min \left(IC(V_{sw,t}, Q_{sw,t}^k) + \sum_{l=1}^L (p_{kl} F_{t+1}^*(V_{sw,t+1}, Q_{sw,t+1}^l)) \right) \quad (4)$$

where k is the discrete flow class in t , l is the discrete flow class in $t+1$ and p_{kl} is the transition probability of runoff class k in t to a runoff class l in t . Figure 13 presents how the transition probabilities are used to generate the expected future cost function from the total costs in $t+1$ in the water value method. Each of the total cost vectors in $t+1$ are multiplied by the respective transition probabilities and summed to form the future cost function in t . The same principle is used to calculate the FCF for the other flow classes.

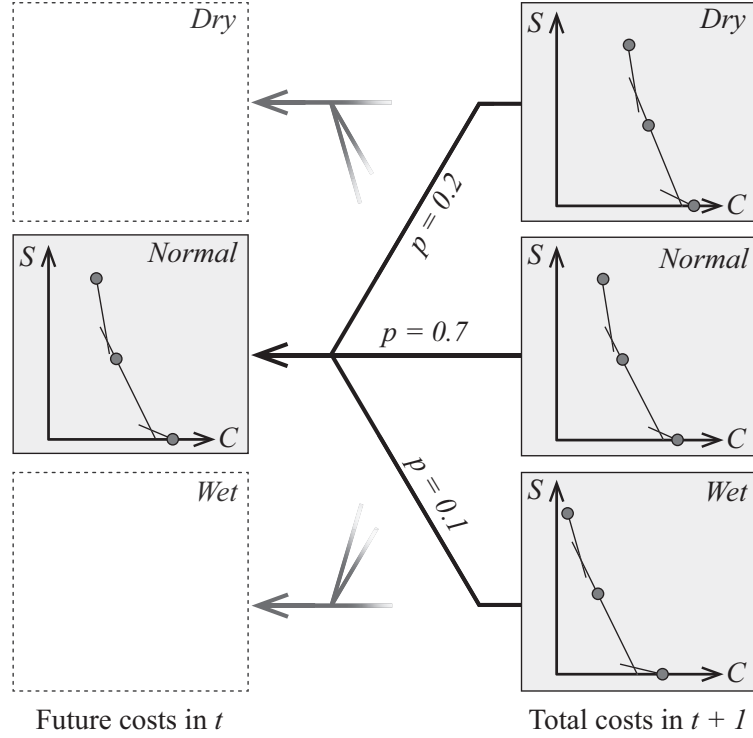


Figure 13: Generation of the expected future cost function for the *Normal* flow class in t , by weighting the total costs in $t+1$ with the transition probabilities p . S is reservoir storage and C is total costs.

The recursive SDP continues backward in time, while storing the minimum total costs and shadow prices for all state combinations. In the fully discrete DP, the end condition can be fixed to any state, thereby avoiding the model emptying the reservoir towards the end. In the water value method, the end condition of the ($FC = 0$) makes it favorable to release all the reservoir water to reduce the immediate costs. To avoid this effect, the model is run backward until equilibrium has been reached, i.e. the inter-annual differences in the water values (shadow prices) become insignificant. As presented in Paper I, the shadow prices from the initial year (furthest away from the end condition), are used as the *equilibrium water values*.

The equilibrium water value table and associated total costs are used as the expected future cost function in a forward moving simulation. With given initial reservoir storage and reservoir inflow and unknown future water availability, the optimization will find the management that minimizes the sum of the IC and EFC. The reservoir inflow reveals the present flow class and thereby also the probabilities of wet, normal and dry flow class in the following month. These probabilities are used to generate the FCF as illustrated in Figure 13. The resulting optimal future reservoir storage is used as initial conditions as the simulation advances to the next stage.

4.2 Water resources systems representation

In this chapter, the SDP framework is applied to the ZRB case. The methods from the three research papers will be presented while pointing to central challenges associated with the method development.

4.2.1 Basin-scale surface water allocation

In Paper I, the water management problem presented in Figure 14 was optimized. The model allocates surface water (*sw*), groundwater (*gw*) and water diverted from the SNWTP to the water users shown in Figure 9. The costs of the immediate management were calculated according to (2), where unsatisfied water demands are associated with marginal curtailment costs. Each of the users was therefore characterized by their water demand and marginal curtailment cost. Reservoir releases generated hydropower benefits and any reservoir releases not allocated to the users were available to the ecosystems.

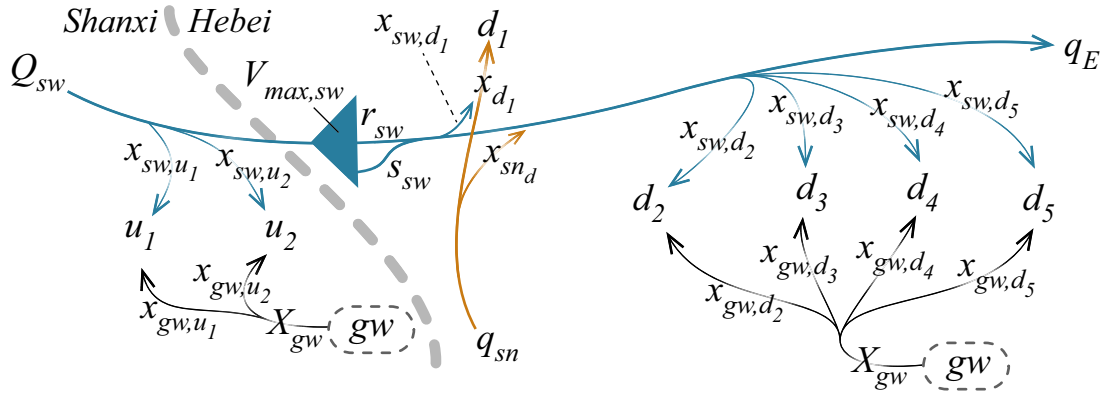


Figure 14: Conceptual sketch of the surface water management problem. Blue arrows are surface water, black arrows are groundwater, and yellow arrows are SNWTP water.

The objective was to minimize the sum of the IC and EFC as presented in (4). The immediate costs follow as:

$$IC(V_{sw,t}, Q_{sw,t}^k) = \sum_{m=1}^M (c_{sw}x_{sw} + c_{gw}x_{gw} + c_{SNWTP}x_{SNWTP} + c_{ct}x_{ct})_{m,t} - r_{sw,t}b_{hp} \quad (5)$$

where c is the marginal costs (CNY/m³), x is the allocated volume (m³/month), r_{sw} is the reservoir release (m³/month) and b_{hp} is marginal benefit from hydropower production (CNY/m³).

The optimization is subject to the following constraints:

$$\left(x_{sw} + x_{gw} + x_{SNWTP} + x_{ct} \right)_{m,t} = dm_{m,t} \quad (6)$$

$$V_{sw,t} + Q_{sw,t} - x_{sw,u,t} = V_{sw,t+1} + r_{sw,t} + s_{sw,t} \quad (7)$$

$$r_{sw,t} + s_{sw,t} = x_{sw,d,t} + q_{E,t} \quad (8)$$

$$x_{sw,u,t} \leq Q_{sw,t} \quad (9)$$

$$x_{sw,Beijing,t} + x_{SNWTP,Beijing,t} \leq Q_{max,SNWTP} \quad (10)$$

$$r \leq R, \quad x_{SNWTP} \leq Q_{SNWTP}, \quad q_E \geq Q_E, \quad V_{sw} \leq V_{max} \quad (11)$$

$$V_{sw,t} \leq V_{max,sw} \quad (12)$$

$$FC \geq \lambda_{1..h} (V_{end} - V_{1..h}) + FC_{1..h} \quad (13)$$

where (6) is the demand fulfillment constraint; (7) is the reservoir water balance with u indexing the users upstream the reservoir, $x_{sw,u}$ is the total surface water allocated to the upstream users and s is the spills (m^3/month) exceeding the hydropower capacity R (m^3); (8) is the mass balance of the reservoir releases, where d is the users downstream reservoirs, q_E is the water leaving the system available to the ecosystems (m^3/month) and Q_E is the minimum in-stream flow constraint (m^3/month); (9) limits the upstream allocations to the runoff; (10) constraints the releases to Beijing with $Q_{max,SNWTP}$ being the upper capacity of the SNWTP canal (m^3/month); (11) are four simple upper and lower bounds where V_{max} is the upper reservoir storage capacity (m^3); (12) is a monthly groundwater pumping constraint with X_{gw} defining the maximum allowed pumping (m^3/month), (13) is the piecewise linear FCF with h discrete reservoir states, $\lambda_{1..h}$ being the shadow prices (CNY/ m^3) from $t+1$ and FC_h the optimal value (CNY) from h in $t+1$.

The sub-problems are strictly linear and convex. The SDP model was programmed in MATLAB using a fast LP solver *cplexlp* (IBM, 2013). Approximately 60 stages (five years) were needed to reach equilibrium. Solving 120 stages on a quad-core laptop required less than 1 minute of computation time.

Table 3: Water demands and water curtailment costs for the water users in ZRB.

	Upstream	Downstream	
Water demands (10^6 m ³ /month)			
<i>Industries</i>	539	543	^a
<i>Domestic</i>	223	864	^b
<i>Maize</i>	569	1,522	^c
<i>Wheat</i>	-	6,089	^c
<i>Beijing</i>	-	1,000	^d
<i>Ecosystems</i>	-	100	^e
Total	1,331	10,119	
Curtailment costs (CNY/m ³)			
<i>Industries</i>	5.3	5.3	^f
<i>Domestic</i>	3.2	3.2	^f
<i>Maize</i>	1.8	2.8	^g
<i>Wheat</i>	-	2.1	^g
<i>Beijing</i>	-	5.5	^h

^aDemands scaled with area, (World Bank, 2001; Berkoff, 2003; Moiwo et al., 2010)

^bBased on daily water demand (National Bureau of Statistics of China, 2011) scaled with the 2007 population from Landsat (Bright et al., 2008)

^cBased on the land cover (USGS, 2013) and irrigation practices collected in the field (Field Report VI). The wheat irrigation demand is evenly distributed in March, April, May and June. Maize is irrigated in July.

^dBased on plan by The People's Government of Hebei Province (2012, (Ivanova, 2011)

^eEstimated deficit in the Baiyangdian Lake (Honge, 2006)

^fEstimate by World Bank (2001)

^gBased on water use efficiency (Deng et al., 2006) and producers' prices (USDA Foreign Agricultural Service, 2012)

^hEstimate by Berkoff (2003)

4.2.2 Estimating the economic value of water

The economic values of the different water uses in the ZRB are central inputs to the optimization scheme. In Table 3, the individual curtailment costs and water demands are listed. Limited data availability prevented characterization of the full user demand curves. Instead a single demand-price point was estimated for each water user.

The agricultural curtailment costs were based on the water use efficiency estimates by Deng et al. (2006), who link irrigation water to increases in crop yield, and the average producers' prices by the USDA Foreign Agricultural Service (2012). The industrial and domestic curtailment costs were based on estimates by the World Bank (2001) and the Beijing average curtailment costs were based on estimates by Berkoff (2003).

4.2.3 Joint surface water – groundwater allocation

In Paper II, an additional state variable was added to the water management problem in paper I. This state variable is used to handle the storage in the groundwater aquifer in the downstream basin and replaces the monthly pumping limit (12). This addition allows modeling the optimal conjunctive management to avoid overdrafting the groundwater aquifer. In Figure 15, the new setup is sketched.

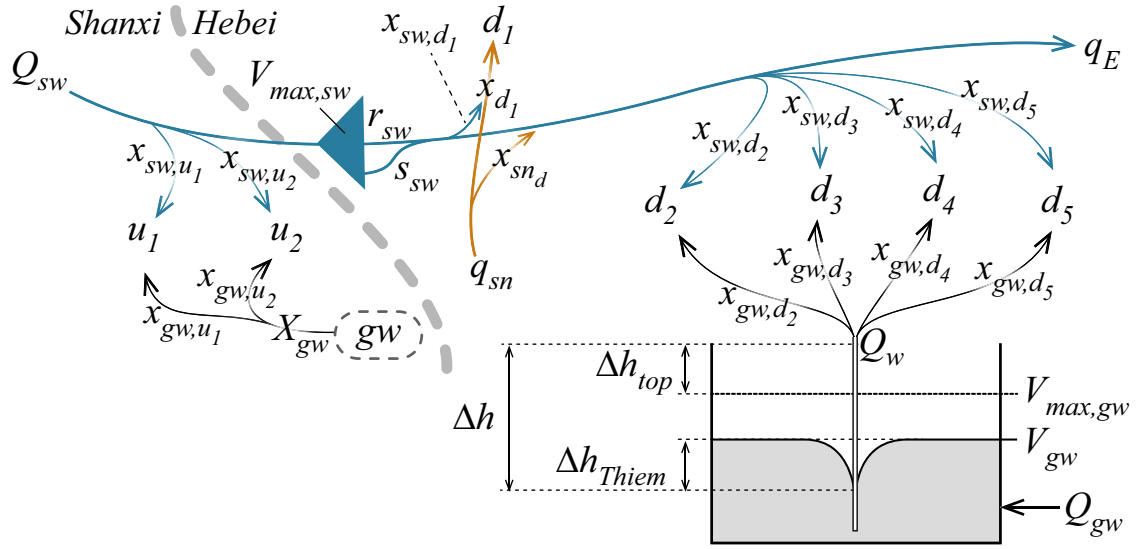


Figure 15: Conceptual sketch of the management problem with head-dependent groundwater pumping costs. Blue arrows are surface water, black arrows are groundwater, and yellow arrows are SNWTP water.

The groundwater aquifer was included as a simple box model. The combined groundwater abstractions by the downstream users contribute to a regional lowering of the groundwater table, equivalent to what has been observed on the NCP. A MIKE SHE groundwater model for the NCP (Marker, 2013) was used to estimate a realistic transmissivity of the groundwater aquifer.

The isolated upstream groundwater aquifer uses a simple average monthly pumping limit equivalent to the one used in Paper I. Including this aquifer as a separate box model would require another state variable, which is computationally infeasible due to the *curse of dimensionality*.

Increased depth to the groundwater table requires additional pump energy to lift the groundwater to the surface. This pump energy was used to link the groundwater table to a marginal pumping. The resulting head-dependant groundwater pumping cost is used to express the IC of the objective function.

The objective function is similar to (4), with an added state variable:

$$F_t^*(V_{gw,t}, V_{sw,t}, Q_{sw,t}^k) = \min \left(IC(V_{gw,t}, V_{sw,t}, Q_{sw,t}^k) + \sum_{l=1}^L (p_{kl} F_{t+1}^*(V_{gw,t+1}, V_{sw,t+1}, Q_{sw,t+1}^l)) \right) \quad (14)$$

with the immediate cost:

$$IC(V_{gw,t}, V_{sw,t}, Q_{sw,t}^k) = \sum_{m=1}^M (c_{sw} x_{sw} + c_{gw} x_{gw} + c_{SNWTP} x_{SNWTP} + c_{ct} x_{ct})_{m,t} - r_{sw,t} b_{hp} \quad (15)$$

The optimization is subject to:

$$V_{gw,t} + Q_{gw,t} - x_{gw,d,t} - s_{gw,t} = V_{gw,t+1} \quad (16)$$

$$x_{gw,u,t} \leq X_{gw,t} \quad (17)$$

$$V_{gw,t} \leq V_{max,gw} \quad (18)$$

$$c_{gw} = f(V_{gw}, x_{sw,d}) \quad (19)$$

and the following constraints from the previous model; demand fulfillment (6), surface water balance (7), reservoir release balance (8), upstream surface water limit (9), Beijing allocation limit (10) and surface reservoir storage capacity, hydropower production capacity and minimum in-stream flow constraints (11). (16) is a groundwater balance constraint, (17) is an upstream groundwater pumping constraint, (18) is an upper groundwater aquifer storage capacity and (19) is the head-dependent groundwater pumping cost constraint.

The marginal groundwater pumping cost was linked to the energy needed to lift the water from the groundwater table to the land surface and the electricity price c_{el} :

$$c_{gw} = P c_{el} = \rho g \Delta h \varepsilon^{-1} c_{el} \quad (20)$$

where P is the specific pump energy (J/m^3), ρ is water density (kg/m^3), g is the gravitational acceleration (m/s^2), Δh is head difference (m) and ε is the pump efficiency (-).

The head difference was included as three different components as illustrated in Figure 15; the distance from the surface to the top of the full groundwater aquifer Δh_{top} , the average regional lowering of the groundwater table Δh_{reg} and the local drawdown cone at the single groundwater wells Δh_{Thiem} estimated as the steady state Thiem drawdown (Thiem, 1906):

$$\Delta h = \Delta h_{top} + \Delta h_{reg} + \Delta h_{Thiem} = \Delta h_{top} + \left(V_{\max, gw} - \frac{V_{gw,t} + V_{gw,t+1}}{2} \right) S_y^{-1} A^{-1} + \frac{Q_w}{2\pi T} \ln \left(\frac{r_{in}}{r_w} \right) \quad (21)$$

where S_y is the specific yield (-), A is the area of the aquifer (m^2), Q_w is the average pumping rate through the ZRB wells ($m^3/month$), T is the transmissivity ($m^2/month$), r_{in} is the radius of influence, and r_w is the radius of the well. Δh_{reg} is calculated from the average storage in t and $t+1$.

Marker (2013) refined a MIKE SHE model of the NCP (Qin et al., 2013) to the ZRB. An average hydraulic conductivity of $1.3 \cdot 10^{-6} m^2/month$ (silty loam, Qin et al., 2013) was found to be realistic. Field interviews showed that the wells typically reach 200 m below surface (field report VI). The downstream aquifer volume was estimated from the downstream area, the thickness and a saturated water content of 0.45 for silty loam (Qin et al., 2013) to $275 km^3$. This results in a specific yield of 0.05. The transmissivity follows:

$$T = \frac{KV_{\max}}{AS_y} = 0.7 \cdot 10^3 m^2/month \quad (22)$$

Erlendsson (2014) estimated the radius of influence to 500 m and a well density of 16 wells/ km^2 . If the wells are evenly distributed, this results in overlapping drawdown cones from 8 surrounding wells. This contribution was included using the principle of superposition.

The optimization problem was implemented in MATLAB. A number of different model implementations were tested in the method development phase. As shown in (21), the groundwater pumping costs depend on the end storage decision variable. When substituted into the objective function, the pumping cost is multiplied with the groundwater allocation decision variable. This non-linear relationship violates the linearity needed for solving the optimization problem with efficient LP.

An alternative linear approach, where the groundwater pumping cost depends only on the initial reservoir storage, was attempted. The model was run with $FC = 0$ for different electricity prices. The resulting immediate costs as a function of the initial reservoir storage are presented in Figure 16. At prices below 2 CNY/kWh, the immediate costs form a strictly convex cost function, suitable for the FCF cost approach shown in Figure 12. However, at higher electricity prices, the pumping costs start to exceed the curtailment costs of the users. This additional curtailment introduces concavity, which makes the Benders cuts piecewise linear FCF approach in Figure 12 infeasible.

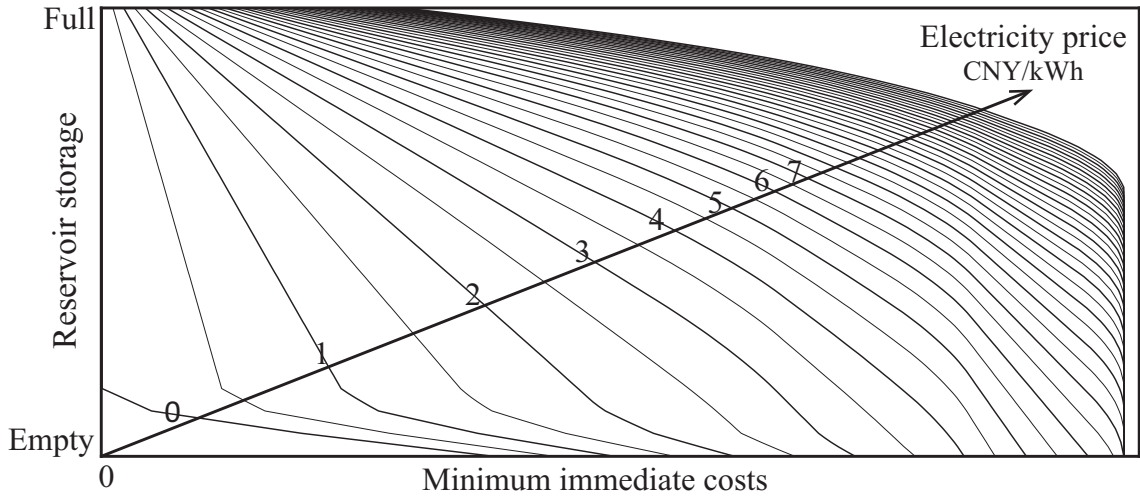


Figure 16: The immediate cost with increasing electricity price. At electricity prices less than 2 CNY/kWh, the costs form a strictly convex piecewise linear function. At higher prices, the shape becomes increasingly concave.

In Figure 17, the resulting FCF based on convex and concave immediate costs, are illustrated. The LP algorithm will search the optimal future cost in the feasible decision space, greater than or equal to the front formed by the linear segments. In the convex situation, the linear segments correctly form the FCF. With concave immediate costs, the linear segments overlap and remove a large part of the feasible decision space.

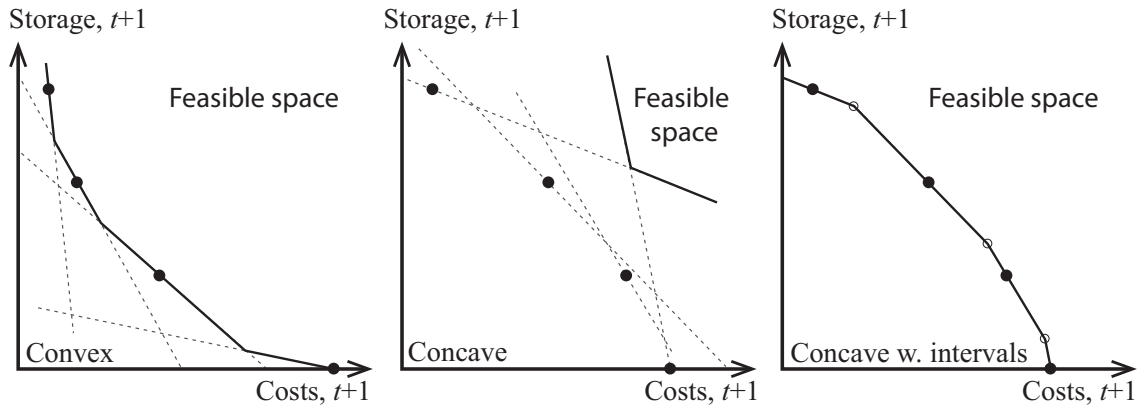


Figure 17: Future cost function based on convex (*left*) and concave immediate costs. The black line marks the feasible decision space, faced by the optimization algorithm. *Middle*: the concave costs remove a part of the feasible space. *Right*: a future cost function, where the linear segments are only binding in intervals.

An alternative setup is to let the line segments be binding only inside intervals defined by intersection points with the neighboring line segments (see Figure 17, right). With a single reservoir state variable as illustrated in Figure

17, this will be trivial to implement. However, in the conjunctive groundwater surface water setup, the FCF is formed by [*surface water states* \times *groundwater states*] 3-dimensional planes. Consequently, it will be non-trivial to define the intersection points.

An alternative strategy, based on the coupled GA-LP framework by Cai et al. (2001) was used to solve the sub-problems. The complicating reservoir end storage variables were outsourced to a GA as presented in Figure 18. The GA searches iteratively for the optimal solution while changing the end storage levels. For every candidate solution, the GA calculates and uses the total costs as performance indicator. For a given candidate solution of reservoir end storages, the reservoir releases are also given and the optimal allocation can be determined with a simple LP. The total costs from $t+1$ are weighted with the transition probabilities to form a two-dimensional [*surface water states* \times *groundwater states*] matrix with EFCs. For every candidate solution, the GA interpolates the EFC illustrated in Figure 18.

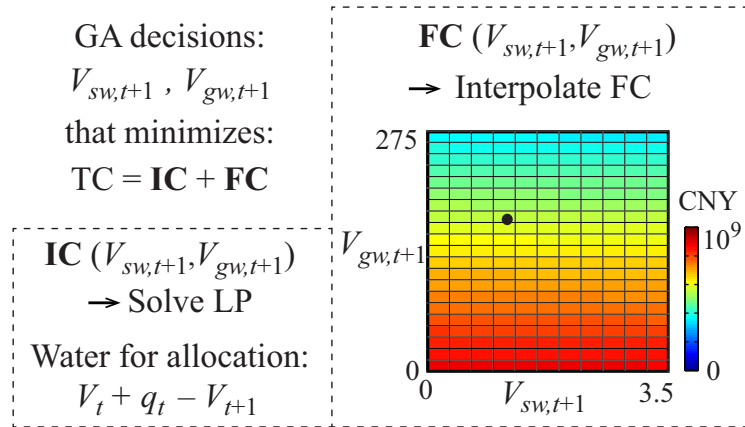


Figure 18: The coupled GA-LP principle

The GA will iterate towards the optimal solution, and the difference between the resulting approximate optimum and the true optimum is determined by a set of user defined stopping criteria. One stopping criterion is a lower threshold on the marginal improvement in fitness value (here the total costs). Other stopping criteria are the maximum number of generations and the maximum computation time. Cai et al. (2001) provided a good overview of the GA functionality.

The optimization problem was implemented in MATLAB using the native *ga* solver and the *cplexlp* (IBM, 2013). Approximately 10 seconds of computation time were needed to solve each sub-problem, and each stage could be

Table 4: Pollution generation data, where α is flexible BOD generation dependent on water allocations, β is BOD generation independent from water allocations and c_{mwwt} is the BOD the marginal cost of removing the generated BOD in the user's return flow

Water user	Node	Quality ^[1] mg BOD/l	α g/m ³	β 10 ⁶ kg	c_{mwwt} CNY/kg
Agriculture	$n_1 + n_2$	10 ^[2]	0.2 ^[3]	-	∞ ^[6]
Industry	$n_1 + n_2$	6 ^[2]	4.1 ^[4]	-	39 ^[7]
Domestic	n_1	0	-	22.5 ^[5]	39 ^[7]
Domestic	n_2	0	-	12.3 ^[5]	39 ^[7]

^[1]Reference BOD concentration criteria before water treatment, ^[2](HRB WRPB, 2008), ^[3]COD from agricultural sector in ZRB (Li et al., 2014), ^[4]annual COD in Hebei Province (IPE Beijing, 2013), scaled with population to ZRB (Bright et al., 2008), ^[5]average BOD generation 67 g/capita/day (McKinney, 2004), ^[6]infinite treatment costs as the farmers cannot treat their diffuse pollution, ^[7]annual industrial COD in Hebei Province, scaled with population to ZRB. A ratio of 0.52 BOD/COD was applied (ADB, 2002).

The objective of this coupled water resources and water quality optimization problem is to minimize the basin-wise water management costs arising from water allocation, water treatment and water curtailment. The objective function is equal to (4) with the IC bringing in the costs associated to water quality in the river:

$$IC(V_{sw,t}, Q_{sw,t}^k) = \sum_{m=1}^M (c_{sw}x_{sw} + c_{gw}x_{gw} + c_{SNWTP}x_{SNWTP} + c_{ct}x_{ct} + c_{wwt})_m - r_{sw,t}b_{hp} \quad (23)$$

where c_{wwt} is the total pollution treatment costs (CNY).

The optimization is subject the following constraints from the previous models; demand fulfillment (6), surface water balance (7), reservoir release balance (8), upstream surface water limit (9), Beijing allocation limit (10), surface reservoir storage capacity, hydropower production capacity and minimum in-stream flow constraints (11) and the piecewise linear FCF (13).

BOD pollution is a major problem in the ZRB and BOD was therefore used to demonstrate the water quality component in the optimization framework. The monthly BOD generation γ_{BOD} (g BOD/month) for each user was defined as:

$$\gamma_{BOD} = \alpha x + \beta \quad (24)$$

where α is the BOD generation dependent on water allocations (g BOD/m³ water allocated to the user), and β is the fixed BOD generation independent of water allocations (g BOD/month).

The total pollution treatment costs were defined as pre-use treatment costs, $c_{pre-wwt}$ (CNY/month) and post-use treatment costs of removing generated pollution from the user's return flow, $c_{post-wwt}$ (CNY/month):

$$c_{pre-wwt} = \begin{cases} x_{sw} (C - C_{ref}) c_{mwt}, & C > C_{ref} \\ 0, & C \leq C_{ref} \end{cases} \quad (25)$$

$$c_{post-wwt} = \begin{cases} (\alpha x + \beta - x_{BOD}) c_{mwwt}, & \alpha x + \beta > x_{BOD} \\ 0, & \alpha x + \beta = x_{BOD} \end{cases} \quad (26)$$

where C is pollutant concentration at the intake point (g BOD/m³), C_{ref} is the user pollution concentration threshold, at which pre-usage treatment is initiated (g BOD/m³ in the river), c_{mwt} is the marginal treatment costs of intake water before use (CNY/g BOD), c_{mwwt} is the marginal cost of removing the generated BOD in the user's return flow (CNY/g BOD), and x_{BOD} is the pollution discharge to the river (g/month). The two treatment costs were assumed to be the same, as only very limited data was available for the case study area.

The pollution concentrations at the two nodes were calculated assuming perfect mixing in the river:

$$C_1 = C_0 + \frac{x_{BOD,j} + \dots + x_{BOD,j}}{r_{sw,t} - (x_{sw,j} + \dots + x_{sw,J})} \quad (27)$$

where C_1 is the BOD concentration at node one (g BOD/m³), C_0 is the pollutant concentration in the reservoir release (g BOD/m³), and j indexes the J users located at node one.

The degradation of BOD was assumed to follow a first order decay:

$$BOD(t) = BOD_0 \exp(-k_1 t) \quad (28)$$

where BOD_0 is the initial BOD concentration (g/m³), k_1 is the deoxygenation rate (d⁻¹) and t is the travel time between the two nodes (days). The BOD concentration at node two is:

$$C_2 = C_1 \exp(-k_1 t) + \frac{x_{BOD,z} + \dots + x_{BOD,Z}}{r_{sw,t} - (x_{sw,j} + \dots + x_{sw,J}) - (x_{sw,z} + \dots + x_{sw,Z})} \quad (29)$$

where z indexes the Z users located at node two.

If the river flow becomes zero, the BOD concentration cannot be quantified (infinite concentration). Instead, a minimum in-stream flow constraint was introduced. This flow constraint was linked to the natural runoff, to obtain both good water quality and some degree of seasonal variation.

The main problem of BOD in a water quality perspective is not the direct toxicological effects, but the associated depletion of dissolved oxygen. In Paper **III**, water quality constraints were therefore set as lower bounds on the dissolved oxygen concentration (DO) rather than on BOD. The Streeter-Phelps equation is a commonly used approach to estimate the DO concentration in the a river, assuming perfect mixing (Streeter and Phelps, 1958):

$$D = \frac{k_1 BOD_0}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t}) + D_0 e^{-k_2 t} \quad (30)$$

where D is the oxygen saturation deficit (g/m^3), k_2 is the reaeration rate (d^{-1}), BOD_0 is the initial oxygen demand of the organic matter in the water (g/m^3) and D_0 is the initial oxygen saturation deficit (g/m^3).

The dissolved oxygen concentration DO (g/m^3) is derived from the saturated oxygen concentration DO_{sat} (g/m^3):

$$DO = DO_{sat} - D \quad (31)$$

As shown in (30), the oxygen deficit is a function of time. The water quality constraint was targeted as the minimum dissolved oxygen anywhere in the river, i.e. the critical time that maximizes D . This was found as the time, where the slope of the first derivative of (30) yields zero:

$$t_c = \frac{1}{k_2 - k_1} \ln \left[\frac{k_2}{k_1} \left(1 - \frac{D_0 (k_2 - k_1)}{BOD_0 k_1} \right) \right] \quad (32)$$

where t_c is the critical time (d).

The saturated oxygen concentration, the reaeration and the deoxygenation processes are all highly temperature dependent (Schnoor, 1996). k_1 and k_2 were therefore temperature corrected (Schnoor, 1996):

$$k = k_{20} \theta^{(T-20)} \quad (33)$$

where k_{20} is the k_1 or k_2 at 20°C , T is the river temperature, and θ is a constant. $k_{1,20}$ was estimated to 0.3 d^{-1} and $k_{2,20}$ estimated to 0.6 d^{-1} , while θ has the value 1.047 for k_1 and 1.024 for k_2 (Schnoor, 1996). DO_{sat} was estimated

with the Weiss baseline DO concentration at zero salinity and one atmosphere (Weiss, 1970; U.S. Geological Survey, 2013). The resulting temperature corrected input data are presented in Table 5.

Table 5: Mean air temperature (China Meteorological Administration, 2009), the oxygen solubility at saturation (Weiss, 1970; U.S. Geological Survey, 2013) and the temperature corrected BOD assimilation and reaeration rates (Schnoor, 1996). *For January, a water temperature of zero degrees Celsius was used.

Month	Mean T °C	DO_{sat} g/m ³	k_1 d ⁻¹	k_2 d ⁻¹
Jan	-2.1*	14.6	0.11	0.36
Feb	1.1	14.2	0.13	0.38
Mar	7.7	11.9	0.17	0.45
Apr	15.3	10.0	0.24	0.54
May	21.2	8.9	0.32	0.62
Jun	26.0	8.1	0.40	0.69
Jul	27.2	7.9	0.42	0.71
Aug	25.8	8.1	0.39	0.69
Sep	21.2	8.9	0.32	0.62
Oct	14.7	10.1	0.24	0.53
Nov	6.3	12.4	0.16	0.43
Dec	0.0	14.6	0.12	0.37

Both pollution concentrations are nonlinear expressions of the decision variables, and therefore an LP solver cannot be used. Instead, the hybrid GA-LP approach from Paper II was applied. By outsourcing the pollutant concentrations at node one and two as decisions for a GA, the remaining decision problem becomes linear.

The optimization problem was implemented in MATLAB using the native *ga* solver and the *cplexlp* (IBM, 2013). The immediate and future costs were formulated as an LP with the two node BOD concentrations as input. Convex future costs allowed integration of the piecewise linear FCF approach presented in Figure 12 and Figure 13 in the LP. The GA used the LP as fitness function while searching for the optimal node concentrations that yield minimum total costs. The Streeter-Phelps equation was supplied as a nonlinear constraint, which forced new candidate solutions to comply with the minimum DO. A flow chart of the algorithm design is presented in Paper III.

The optimization sub-problems faced by the GA are highly non-linear and with multiple local minima as illustrated by the 3D-plot of the decision space in Figure 20. The *ga* settings were selected based on tests to ensure that the *ga* consistently found the global minimum.

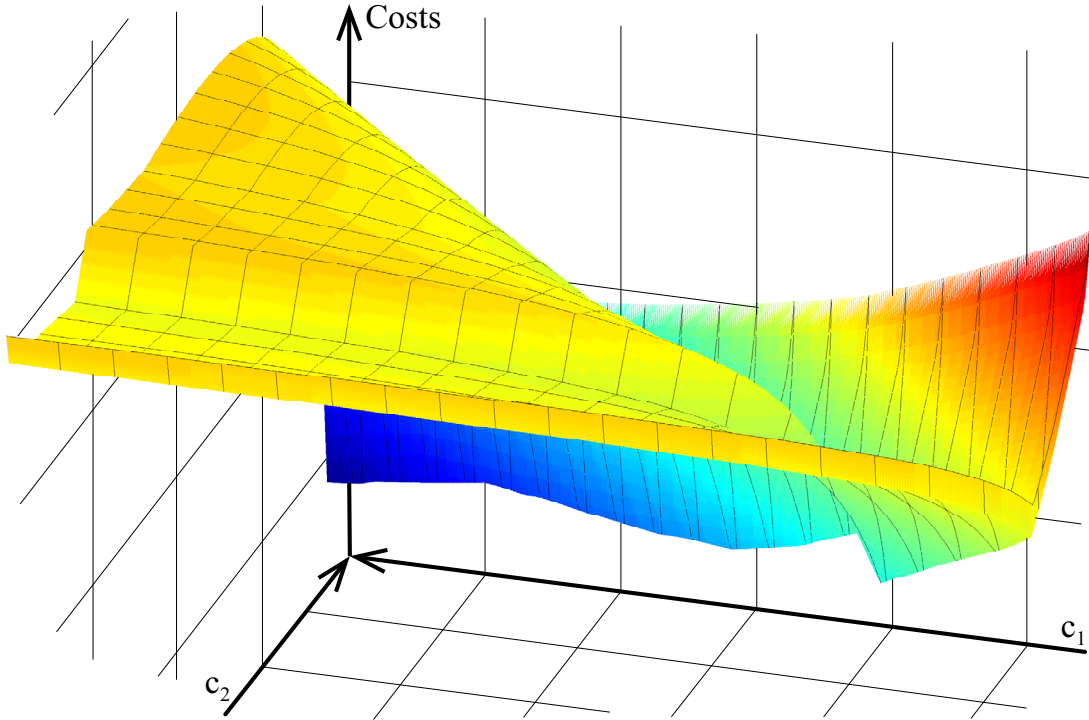


Figure 20: Total costs as a function of the BOD concentration at node 1 and 2 in a single optimization sub-problem. C_1 and C_2 are the two node concentrations (increasing in the direction of the axis arrow).

The high level of complexity caused the *ga* computation time to be three to four times longer than the Paper II model (30-40 seconds per sub-problem). With one state less than in Paper II and with full parallelization of each stage, the computation time needed was approximately one hour per model year. Equilibrium water values were reached up to 120 stages from the end-condition bringing the computation time to approximately ten hours per scenario and climate period.

4.3 Application in decision support

The equilibrium water value tables and related total costs are the main outcomes from the three optimization models. As described in Chapter 4.1.4, these outputs can be used to guide a forward moving simulation with uncertain future water availability.

The simulation is the last step of the 3-step modeling framework presented in Figure 21. The rainfall-runoff model and particularly the optimization model are computationally very demanding, but can also be run separately from real-time management. These models can be updated, e.g. annually, or if the system infrastructure or user setup changes. The simulation models in Paper II and III are much faster and take only 10-20 seconds per month on a standard laptop. In principle, the simulation problem, equilibrium water value tables and the total costs could be coded in a smartphone app and run one-stage-ahead in every month, feeding the simulation with the present reservoir storage and runoff.

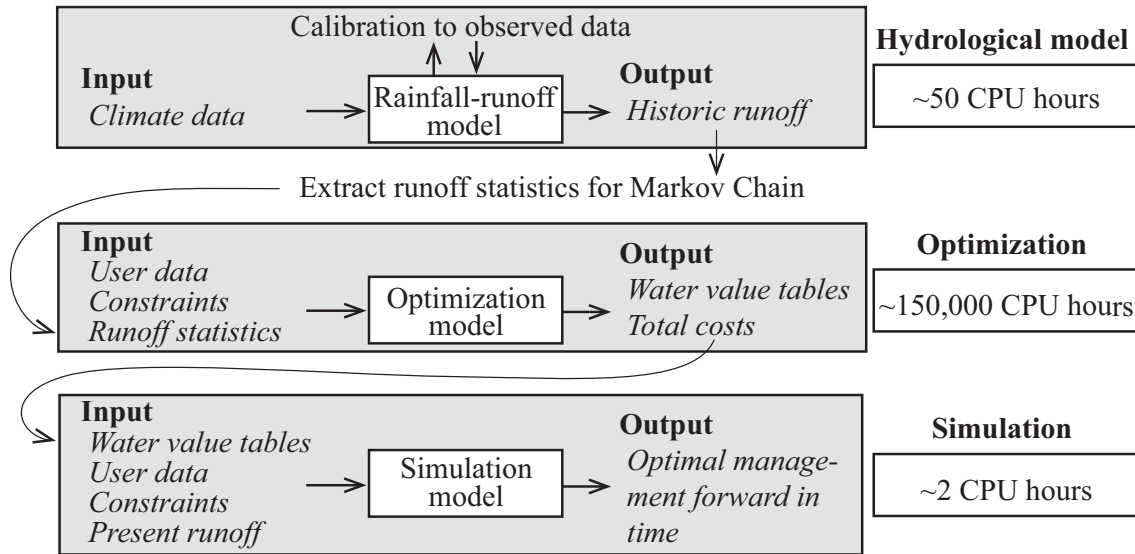


Figure 21: Overview of the 3-step modeling framework and the associated computation times from the model in Paper II. The simulation time is for a 600 stages (50 years) run.

In this PhD, the simulated 51 years of runoff were used as uncertain input to the simulation model. The simulation models were used to compare the performance of various model alternatives, where paper I and II demonstrated the impacts of the SNWTP and Paper III focused on the impact of compliance to different water quality targets.

5 Overview of main results

In this chapter, the main findings of three consecutive studies, based on the methods presented in Chapter 0, will be highlighted. The chapter will be a comparison of the three studies and focus on the general findings. For detailed results and discussion, see Paper I, II and III.

5.1 Water value tables

Equilibrium surface water value tables from three comparable scenarios, one from each paper, are presented in Figure 22. The Paper I results are for a scenario with monthly groundwater pumping limits and minimum in-stream flow constraints of 100 million m³ in July, the Paper II results are for a scenario with Thiem steady state drawdown and minimum in-stream flow constraints equal to the Paper I setup and the Paper III results are for a scenario with water quality grade II (minimum 6 mg O₂/L), a constant groundwater price at 2.5 CNY/m³ and 5% minimum-instream flow for ecosystems. These scenarios will be used through this chapter.

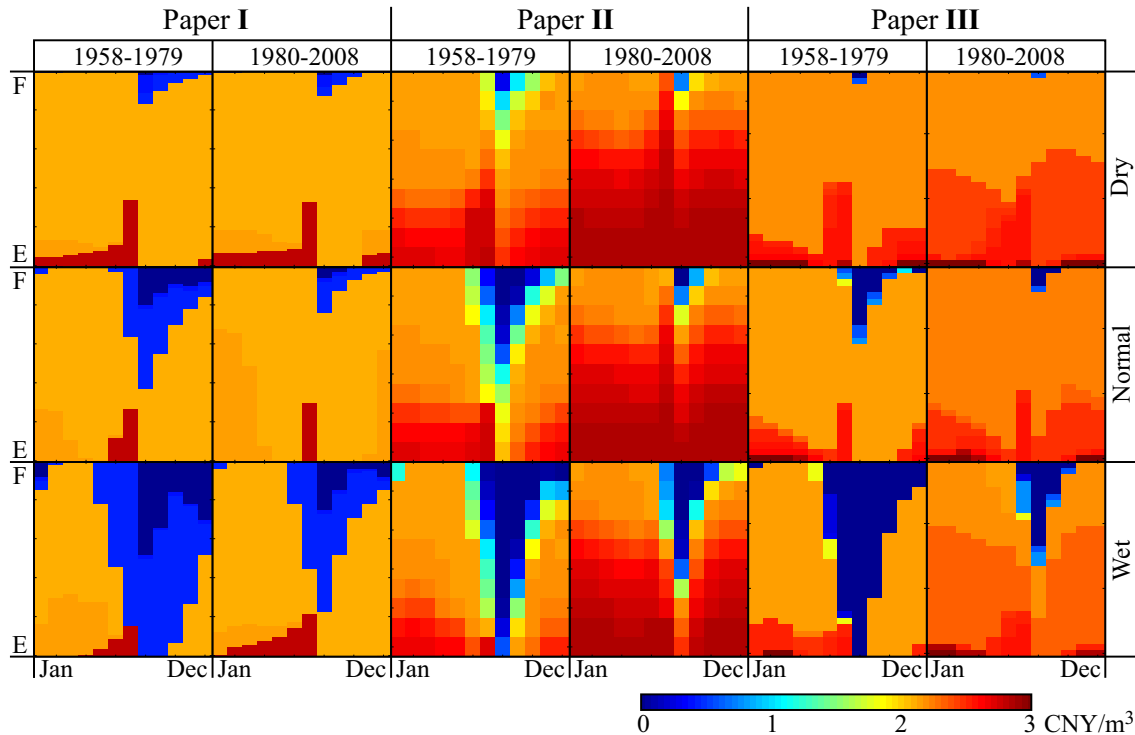


Figure 22: Surface water value tables from the three studies where E is empty and F is full reservoir storage and *Dry*, *Normal* and *Wet* are the Markov Chain flow classes. The water values from Paper II are shown for a fixed groundwater state at 100 km³ (36% full).

The equilibrium water values vary between 0 to 3 CNY/m³, with the highest values at low reservoir storage. Lower water availability in the 1980-2008 climate increase the water scarcity, which is reflected in higher water values. Similarly, the water values also increases from *Wet* to *Dry* flow classes. High water demands and low runoff in the spring increases the values, whereas high runoff and low demands during the summer months reduce the value of storing water for later use.

The water values in Paper II are generally highest, which is a result of the selected low initial groundwater storage. As presented in Paper II, the long-term equilibrium groundwater table is close to the surface (full groundwater aquifer). At equilibrium, the groundwater shadow prices were found to be stable at 2.2 CNY/m³, independent of the surface water storage. At groundwater storages below equilibrium, the groundwater value increases, which stimulates recovery of the groundwater table. For groundwater storage at 100 km³, the groundwater value is approximately 3 CNY/m³. This high groundwater value is reflected in the surface water values.

5.2 Water management scenarios

The simulation phase in Paper II was initiated from different initial groundwater storage levels to model the optimal policy, while refilling the groundwater aquifer. Figure 23 summarizes the development in the groundwater table for four different initial groundwater storage levels. Another simulation from Paper III is also presented. This study used a fixed groundwater price, and the management will hence not automatically adjust to the groundwater

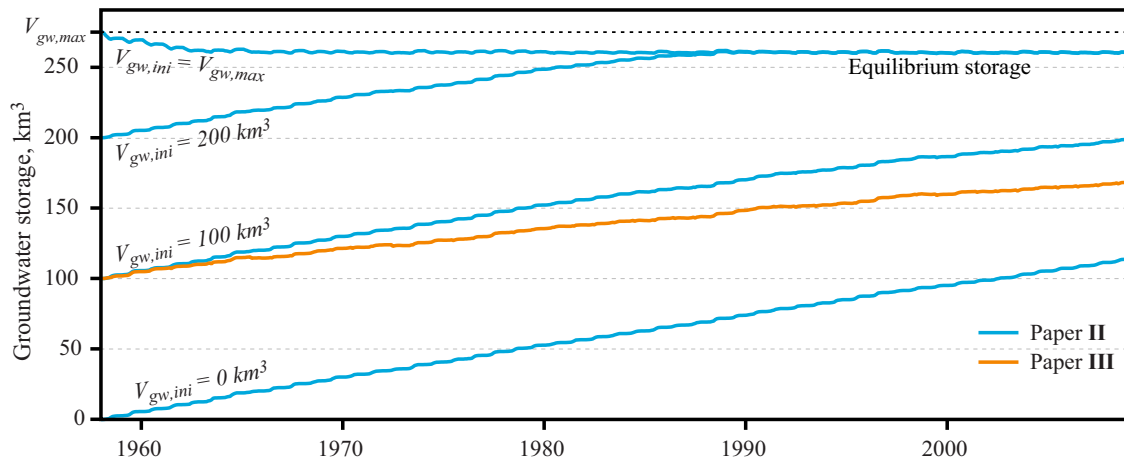


Figure 23: Recovery of the groundwater table from different initial storage levels. Note that the Paper III recovery is not linked to any initial groundwater storage level.

storage. If the groundwater price is kept above the long-term equilibrium price, the groundwater aquifer will start to spill water at some point further into the future.

The groundwater prices of the last unit of water allocated is presented in Figure 24. For Paper II, this price is the user's price of groundwater, i.e. the optimal water price if a water market was introduced. The two other papers used a fixed groundwater price throughout the period as indicated in the figure. The groundwater-state dependent water values in Paper II reveal that the optimal policy would be to gradually lower the groundwater price as the aquifer storage increases.

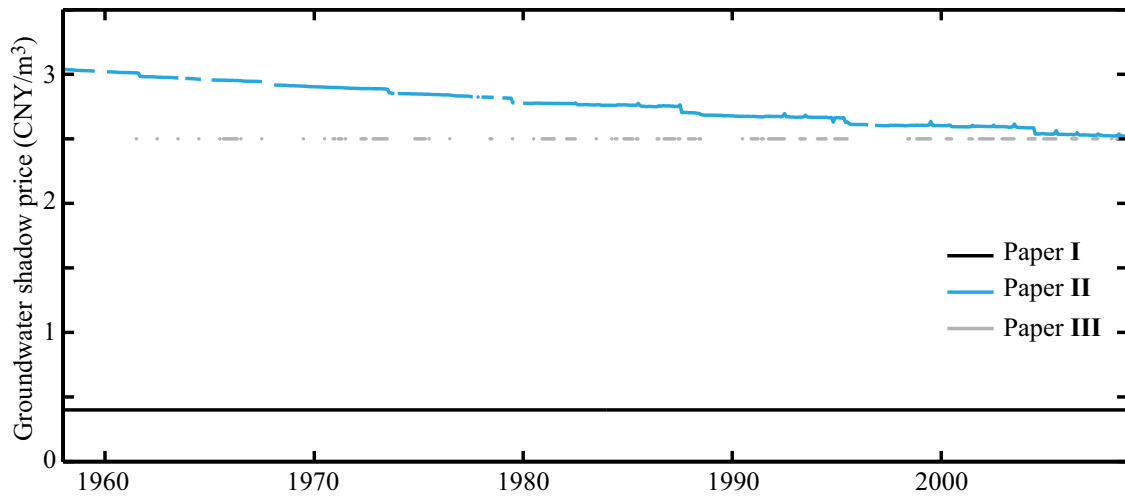


Figure 24: Groundwater prices for the last unit of allocated groundwater in the three models for comparable scenarios. Gaps indicate no allocation.

As illustrated by the gaps in Figure 24, the users in Paper II received groundwater more frequently than the users in Paper III. Despite this difference, the volume of groundwater allocated in the Paper III simulation was largest. This can be explained by two effects. First, the Thiem steady state drawdown in Paper II caused an almost even distribution of groundwater pumping, as the model attempted to avoid expensive pumping from deep drawdown cones. Second, the water quality constraint in Paper III increased curtailment of the users as a measure to reduce the generated BOD, hence reducing the need for groundwater.

The average annual surface water shadow prices for the three studies are presented in Figure 25. As also expected from the equilibrium water value tables in Figure 22, the water values for the Paper I simulation are lowest. The two other studies show comparable surface water values. Despite of this

similarity, the total costs of the Paper III simulation were significantly larger than in the two other studies, as presented in Figure 26. The total costs peak during the first half of the year as presented Figure 27. This is a result of 85% of the water demands being concentrated between March and July while the rainy season peaks in August.

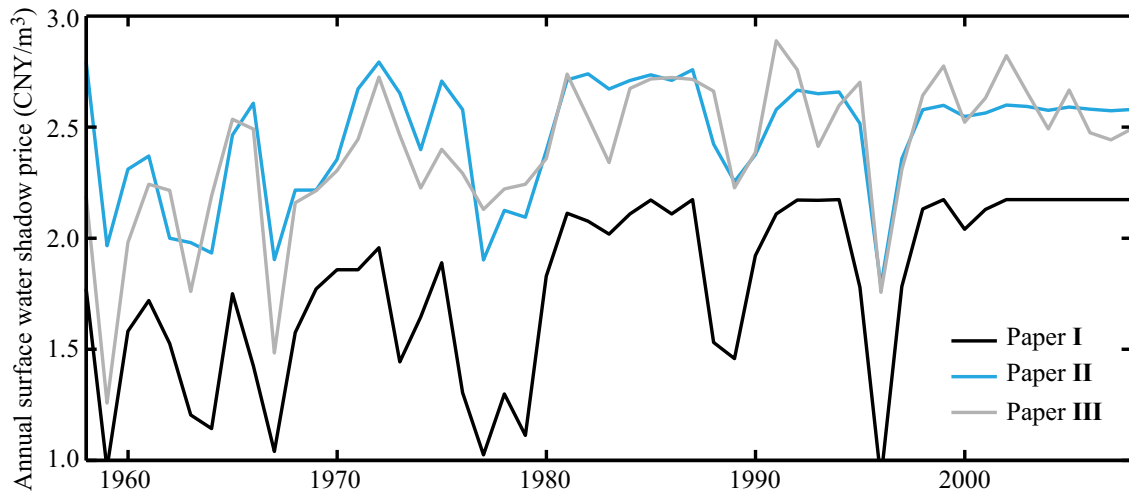


Figure 25: Annual average shadow prices for the last unit of allocated surface water in the three models for comparable scenarios.

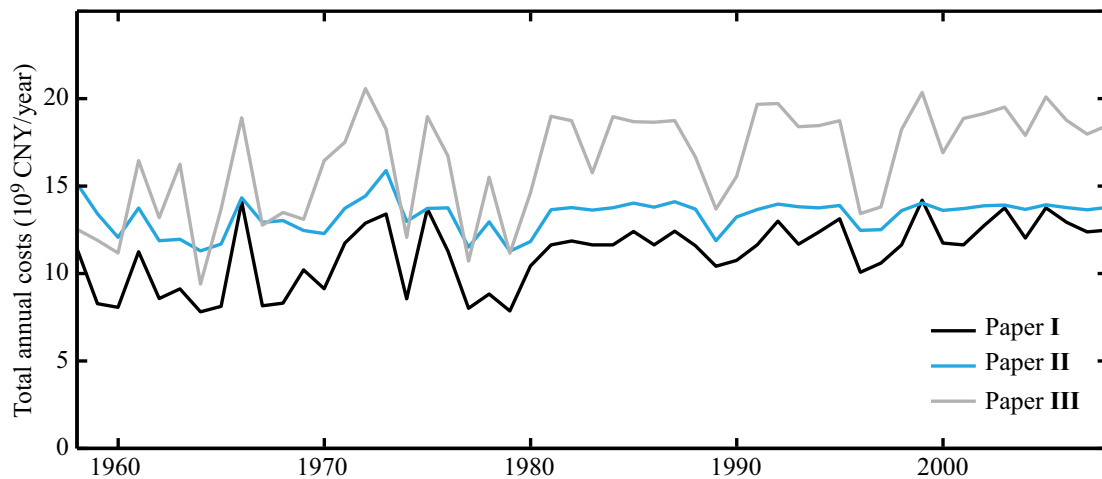


Figure 26: Annual total costs for the three models for comparable scenarios.

The costs associated with compliance to water quality constraints are particularly large during periods with low water availability. A central finding from Paper III was the importance of cost-effective dilution of the BOD in the river, as a measure to comply with the water quality constraint. An alternative mitigation measure was to shift surface water allocations to the

users at node two, thereby utilizing the water for dilution of node one BOD discharges. As shown in Figure 27, the simulated costs in Paper III were significantly higher than in the two other studies during the dry period in late fall and winter in some years. This showed that the model was forced to reduce the BOD discharges in dry month by either increased curtailment of the water users or by increased BOD removal.

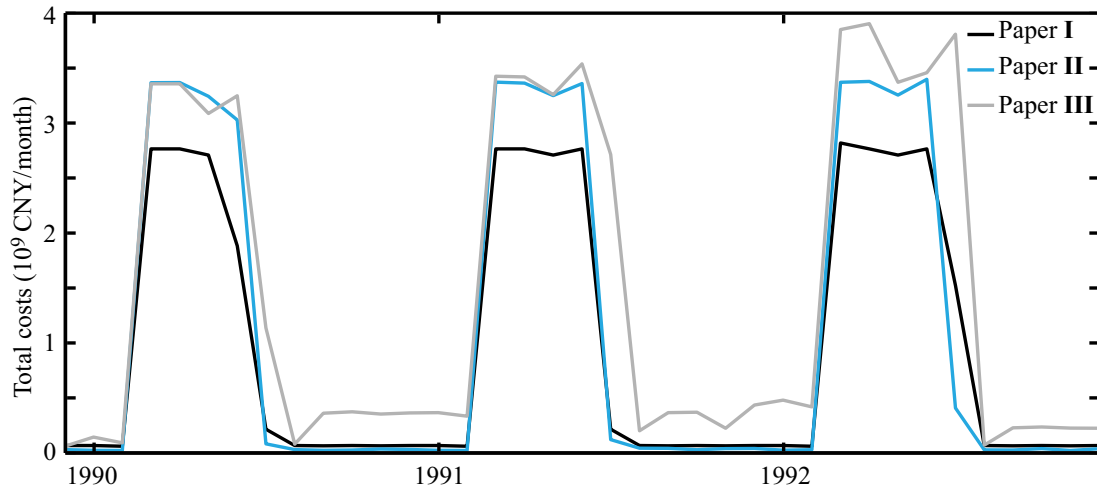


Figure 27: Monthly total costs for the three models in the years 1990, 1991 and 1992. Paper I: Monthly groundwater pumping limit and minimum in-stream flow requirements; Paper II: Initial groundwater storage at 100 km³ (36% full) and with Thiem drawdown and minimum in-stream flow requirements; Paper III: Water quality grade II, fixed groundwater price at 2.5 CNY/m³ and minimum in-stream flow requirements at 5% of natural runoff.

The three models were used to compare the economic performance of a number of scenarios. Table 6 summarizes the resulting total costs and thereby provides important insight in the economic impacts of potential future water management in ZRB.

Paper I and II focused on assessing the economic benefits of the SNWTP. A comparison of the total costs with and without the SNWTP, showed that the marginal benefit of the share of SNWTP water delivered from the Yangtze River to the ZRB and Beijing was 4.7 CNY/m³ with a standard deviation of 0.2 CNY/m³. This value is highly dependent on how large a share of the water that is made available to the basin. Ideally, the boundary conditions of the hydroeconomic model should be expanded to include all river basins that receive water from the SNWTP. Thereby, the optimal distribution and the true value of the SNWTP could be estimated.

Table 6: Simulated average total costs for selected scenarios, where **S1** is pre-2008 (before the SNWTP), **S2** is 2008-2014 (SNWTP finished from ZRB to Beijing), **S3** is post-2014 (SNWTP completed), **B100** is minimum flow of 100 million m³ for Baiyangdian Lake in July, **5%** and **20%** are the minimum in-stream flow as a percentage of the natural runoff, **ub** is monthly upper bound on groundwater pumping, **T** is Thiem steady state drawdown, **ini100** is initial groundwater storage of 100 km³ (other scenarios are for equilibrium storage) and **c2.5** is for a fixed groundwater price at 2.5 CNY/m³ and I, II, III, IV and V are the minimum water quality grade constraints.

	SNWTP	Ecosystem	Groundwater	Water quality	Total costs 10 ⁹ CNY/year
Paper I	S1	B100	ub	-	17.3
	S2	B100	ub	-	13.8
	S3	B100	ub	-	11.4
	S3	-	-	-	3.1
	S3	B100	-	-	3.1
	S3	-	ub	-	11.1
Paper II	S1	B100	T	-	14.9
	S2	B100	T	-	11.7
	S3	B100	T	-	8.6
	S3	B100	T ini100	-	13.1
	S3	-	no T	-	8.4
	S3	-	T	-	8.5
Paper III	S3	5%	c2.5	-	15.6
	S3	5%	c2.5	V	16.2
	S3	5%	c2.5	IV	16.3
	S3	5%	c2.5	III	16.4
	S3	20%	c2.5	III	17.0
	S3	5%	c2.5	II	16.4
	S3	5%	c2.5	I	16.9

The cost of forcing a minimum in-stream flow for the ecosystems has also been investigated through comparison of the scenarios. Paper I and II estimated the marginal cost to 1.2 CNY/m³ with a standard deviation of 0.2 CNY/m³. This represents the marginal economic cost of diverting 100 million m³ water to the Baiyangdian Lake from the ZRB in every July. Other scenario runs can be used to map the costs for diversion in other months. Finally, a similar hydroeconomic optimization approach can be applied to the neighboring river basins, to identify the most cost-effective policy.

In Paper I, a scenario run identified the costs of water management, while considering only the immediate groundwater pumping costs to be 3.1 billion

CNY/year. In Paper **II**, a scenario with the long-term sustainable groundwater management, i.e. the long term average abstraction does not exceed the long term average recharge, resulted in 8.6 billion CNY/year, given the groundwater storage is at equilibrium.

The long-term optimal policy from the present overdrafted groundwater aquifer was estimated by a scenario with the initial groundwater storage at 100 km³. Here the total costs increased to 13.1 billion CNY/m³. The cost of ending groundwater overdraft is thereby on the order of 10 billion CNY/year. This exceeds by far the immediate management costs. Including the future costs in the present management remains one of the key challenges for the decision makers of the ZRB.

The scenarios in Paper **III** were used to map the costs of complying with the Chinese water quality standards (HRB WRPB, 2008). The total costs of the baseline scenario without consideration of water quality were 15.6 billion CNY/year. The significantly higher minimum in-stream flow in Paper **III** increased water scarcity and thereby water curtailments. This explains the increased costs compared to Paper **II**. The additional costs of complying with the lowest water quality class (grade V) were found to be 0.6 billion CNY/year. Compliance to the best class (grade I) was estimated to 1.3 billion CNY/year. The additional running costs of meeting water quality criteria were therefore found to be small compared to the costs of ending groundwater overdraft.

5.3 Application in decision support

The scenario results in Chapter 5.2 demonstrate the large potential for application of the models in decision support. Quantification of the economic impacts of management alternatives improves the decision makers' knowledge and allows them to make better informed decisions.

While Paper **I** demonstrated application of a simple and computationally efficient hydroeconomic model, Paper **II** and **III** expanded the approach to deal with the more complex challenges faced in the ZRB. As demonstrated in Paper **III**, water resources and water quality management are highly coupled. Paper **III** builds on knowledge from the two previous studies and represents the type of multi-disciplinary approaches needed to inform IWRM in the ZRB.

An obvious application of the developed modeling framework is in the context of the No. 1 Document. As demonstrated in this PhD study, a joint hy-

droeconomic modeling framework can integrate the goals as constraints for an optimization and inform optimal management, while complying with these constraints. Thereby, the most cost-effective management can be found across the traditionally separate disciplines of water efficiency, water allocation and water quality management.

As this PhD study has solely focused on identifying the optimal management, a minimum effort has been put on the actual implementation. As mentioned in Chapter 2.2, water taxation and compensation, are suggested as regulative tools for the decision makers. Alternatively, the decision makers can try to enforce the optimal policy with simple rules or law-based regulation. Finally, water quotas can be used to distribute the resources between the users. A recent example is a pilot project in the ZRB, where integrated circuit cards are being introduced to carry the quota allowed for each well (Swiss Water Partnership, 2015). This will allow detailed allocation of water to the end-users.

5.4 Limitations

The primary focus of the PhD project was put on the method development, and the parallel data collection attempted to establish a realistic dataset for demonstrating the method. Given the short time frame of this PhD project, several assumptions and simplifications were needed. Secret data, language barriers and the complex institutional setup were major challenges in the data collection and made a careful validation of the collected data difficult.

The natural water availability is a highly important input for the optimization models and was based on a simple rainfall-runoff model. The modelled natural water availability is difficult to validate, as measured runoff reflects the present management. It is, however, expected that the decision makers have better insight in the natural water availability or at least in the water available for allocation.

The user water demands, water curtailment costs, BOD generation and treatment costs were also simple estimates. Ideally, realistic water demand functions should replace the user demand and curtailment cost. Within the proposed framework, the demand function can be represented by a stepped function with multiple curtailment costs and demands. A finer user representation is feasible within the optimization framework, allowing for representation of, e.g., rural and urban users, various industrial sectors and more crops and detailed BOD generation. Another expansion could focus on linking user de-

mands, particularly the irrigation demands, to the runoff class. Again, limited time and data availability prevented this refinement of the method.

Another source of uncertainty is the modeling framework itself. The *curse of dimensionality* associated with the SDP framework prevents expansion of the models to multi-reservoir management problems and forced spatial aggregation of the system. While this was considered a realistic assumption in the ZRB, the actual impacts were not evaluated with a multi-reservoir optimization approach such as SDDP. The complex non-convex and nonlinear objective problems of Paper II and III, in combination with multiple reservoirs, are difficult to overcome with existing optimization solvers.

In Paper III, the marginal groundwater pumping cost was fixed to a level, which motivated an overall recovery of the groundwater table. Fixing the pumping cost is close to the optimal policy, particularly with short planning periods. However, dynamic pumping cost responses to monthly pumping cannot be captured, which results in unrealistic high monthly pumping rates. Ideally, a combination of the Paper II and III models is preferred. This will distribute groundwater allocations to more years and better represent the true pumping costs. Further, a combined model will allow for a gradual lowering of the pumping costs as the groundwater table recovers. This coupling might be feasible for small aquifers, where equilibrium water values can be reached within, e.g., 20 years of backward iteration. However, the ZRB aquifer is large relative to the water demands, and more than 150 years of backward iteration was needed to reach equilibrium. Combining the two models is therefore expected to become computationally infeasible.

In Paper I, an uncertainty analysis based on Monte Carlo simulations was carried out. The optimization model was fast and allowed for a large population size. The uncertainty analysis was used to quantify the impact of uncertainty in the input data on the simulated total costs. The resulting standard deviations were between 15% and 33%, and thus in the same range as the input uncertainty. A reduction of the input uncertainty is therefore expected to lead to a proportional reduction of the output uncertainty.

The models of Paper II and III are significantly more computationally demanding. Large numerical models provide substantial computational challenges in traditional uncertainty analysis. With up to 150,000 CPU hours needed for a single model run, the author is not aware of any suitable approach. Instead, a simple local sensitivity was used to rank the input data af-

ter sensitivity. One approach could be to downscale the problem and thereby reduce the computation time per model run. Given the limited time available in this PhD, this remains a yet unresolved problem.

6 Conclusions

The goal of this PhD study was to expand existing hydroeconomic approaches to address highly coupled water management problems of surface water, groundwater and water quality management. The proposed method is to formulate the water management as a joint optimization problem that minimizes basin-wide water supply costs subject to a water demand fulfillment constraint. This approach turns the complex water management problem into a single objective optimization problem.

The method was successfully implemented to a complex Chinese river basin water management problem. The first implementation used the water value method, a variant of stochastic dynamic programming for a simple formalization of the management problem. The resulting water value tables were found to be efficient and illustrative tools to guide water management and provided a quantitative understanding of the water conflicts. The optimization model runtimes were short and allowed for a detailed uncertainty analysis of the framework. The model results showed that the water users will keep pumping groundwater until their demands are fulfilled, unless groundwater access is restricted. Further, the results showed that the middle route of the South-to-North Water Transfer Project will impact optimal water resources management and help to reduce water scarcity.

In the second implementation, a dynamic groundwater aquifer was added to model the effect of head-dependent groundwater pumping costs. The study showed how a hydroeconomic optimization approach can be used to derive a pricing policy to bring an overexploited groundwater aquifer back to a long-term sustainable state. Non-convexity caused by the complex objective function was accommodated with the use of a hybrid genetic algorithm – linear programming formulation. This implementation allowed extension of the method to include stationary Thiem local drawdown cones. The water value method showed that groundwater values at equilibrium were independent of the time of the year, the surface water storage and the inflow class. This knowledge can be used to simplify coupled surface and groundwater management as demonstrated in the last implementation. Further, the results showed that the dynamic groundwater aquifer served as buffer and allowed for overexploitation in dry years. This greatly reduced the scarcity costs and stabilized the user's water prices. Despite computationally heavy, stochastic dynamic programming was found to be highly customizable and adequate to solve complex nonlinear objective functions.

The third implementation demonstrated how complex water quality constraints can be included in the water resources management model. The framework was built on a similar hybrid genetic algorithm – linear programming approach, but with a highly simplified groundwater module with a fixed user price as suggested by the second study. Generation of pollutants modelled as biochemical oxygen demand was implemented with constraints targeting downstream minimum dissolved oxygen, computed with the Streeter-Phelps equation. Despite a non-linear objective function and non-linear constraints, the stochastic dynamic programming-based optimization problem was computationally feasible. The results showed that surface water allocations were shifted to the users furthest downstream in the system to utilize the surface water for dilution. Similarly, the releases for ecosystems consistently exceeded a minimum constraint for scenarios with strict water quality constraints. The increase in the total costs was small compared to the scarcity costs, but the significant changes in the optimal management underlined the importance of coupling water quality to traditional water quantity management studies.

The three proposed methods are highly flexible and can be used to inform integrated water resources management in complex coupled systems with up to two reservoir state variables. The modeling framework couples traditionally separate disciplines and represents the type of integrated assessments needed to solve the water challenges on the North China Plain, in context of the China 2011 No. 1 Central Policy Document. Application is, however, not limited to the North China Plain and the method has great potential for application in water scarce areas around the globe.

7 Future research

Future research should address the limitations and continue the development of the proposed modeling framework. The author suggests that future research is focused on, but not limited to, the following aspects related to the case study:

- Better estimates of the natural water availability, particularly with focus on more realistic modeling of groundwater recharge and verification of the rainfall-runoff model. This will make the management model more realistic without additional computational costs.
- Improved data for the case study area, ideally with the authorities guiding to realistic assumptions and constraints. This will allow for a more realistic representation of minimum in-stream flow constraints, SNWTP scenarios and water demands.
- Introduction of water demand functions, approximated by stepped functions of multiple curtailment costs and water demands. This will enable a more realistic dynamic water management with more complex allocation patterns at an expected low computational cost.
- Linking water demands, particularly from irrigation agriculture, to the Markov Chain flow classes. The irrigation demands are highly affected by the precipitation, and establishing a link to the flow class will make the model more realistic without additional computational costs.

While these aspects can be targeted in a continued theoretical study, another central aspect for the future is actual application of hydroeconomic modeling to a real case. Despite the significant potential of past hydroeconomic studies, practical application in decision making is limited. Future research related to the field of hydroeconomics should focus on:

- Assessment of model uncertainty and the robustness of the model results. Mapping of uncertainty is central before the methods are applied in real decision support.
- Better utilization of the increasing amount of real-time data available (water use efficiency, evapotranspiration etc.) to yield better predictions of water demands and water availability. Remotely sensed data should increasingly be used to inform the hydroeconomic models.

- Expansion of the model framework to cope with more aspects of the management problem, e.g. water-energy nexus, food, power. This coupling is not trivial, but will greatly help to jointly manage our resources sustainably.
- Development of validation techniques to assess the performance when hydroeconomic models are applied in real decision making. In theoretical studies, the curtailment costs are a central part of the total costs. These costs are, however, not easy to quantify in reality.

Demonstration through more theoretical case studies, increased focus on development of joint management models and quantification of model uncertainties are expected to bridge the road to practical application.

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9 Papers & Field reports

- I** Davidsen, C., Pereira-Cardenal, S.J., Liu, S., Mo, X., Rosbjerg, D., Bauer-Gottwein, P., 2014. Using stochastic dynamic programming to support water resources management in the Ziya River basin. In press.
- II** Davidsen, C., Liu, S., Mo, X., Rosbjerg, D., Bauer-Gottwein, P., 2015. The cost of ending groundwater overdraft on the North China Plain. Manuscript.
- III** Davidsen, C., Liu, S., Mo, X., Rosbjerg, D., Holm, P.E., Trapp, S., Bauer-Gottwein, P., 2015. Hydroeconomic optimization of reservoir management under downstream water quality constraints. Manuscript.
- IV** Field report 1: June 2012
- V** Field report 2: July 2012
- VI** Field report 3: March 2013

In this online version of the thesis, the three papers (**I-III**) are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

DTU Environment
Technical University of Denmark
Miljøvej, Building 113
2800 Kgs. Lyngby
Denmark

info@env.dtu.dk.

IV

Field Report 1, June 2012

Claus Davidsen

Field Report 1, June 2012

Author: Claus Davidsen



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1 Introduction

On 15 June, 2012 a team of researchers from DTU Environment and CAS IGSNRR attended a joined field trip by car to the Ziya River Basin on the North China Plain. The field trip team was:

- Claus Davidsen, PhD student, DTU Environment and CAS IGSNRR
- Dan Rosbjerg, professor emeritus, DTU Environment
- Peter Bauer-Gottwein, associate professor, DTU Environment
- Xingguo Mo, professor, CAS IGSNRR
- Zhonghui Lin, post doc at CAS IGSNRR

The scope of the field trip was to obtain first-hand knowledge about the area, verify observations from Google Earth and to assess flow levels and river channels. This field report summarizes the findings from the trip.

2 Management of the Ziya River basin

Water management in the Ziya River basin has historically focused on mainly 3 areas (here in prioritized order); Flood control, Water allocation, Pollution.

After huge floods of the North China Plain (NCP) in 1950s and 1960s it was decided to put focus on flood control of the Haihe River and in particular Ziya River basin. The strategy has been to cut the peak flows with reservoirs, limit floods to temporary retention basins using dams and finally to extend the capacity of the rivers and thereby enabling them to carry the water to the Bohai Gulf as quickly as possible. The Ziya River basin has 5 large reservoirs, 13 medium reservoirs and 44 small reservoirs with a combined capacity of 4.1 billion m³ (Ministry of Water Resources and Asian Development Bank, 2005).

The 2 large reservoirs Gangnan and Huangbizhuang help cutting the peak flow of the Hutuo River. Downstream the reservoirs the capacity of the river has been increased. Further, the natural river route to Tianjin has been cut and replaced with a channel and spillway to the junction with Fuyang River. In total the Hutuo River can carry 3500 m³/s (HWCC, 2012). See Figure 1.

In the Fuyang River, the many tributaries carrying water from the Taihang Mountains to the NCP have been cut with dams. The 3 large reservoirs are

Zhuzhuang, Lincheng and Dongwushi with a combined capacity of 768 million m^3 but also many smaller reservoirs, with volumes reserved for flood events. The New Fuyang Channel adds capacity and the Fuyang River can carry 3340 m^3/s to the junction with Hutuo River (HWCC, 2012).

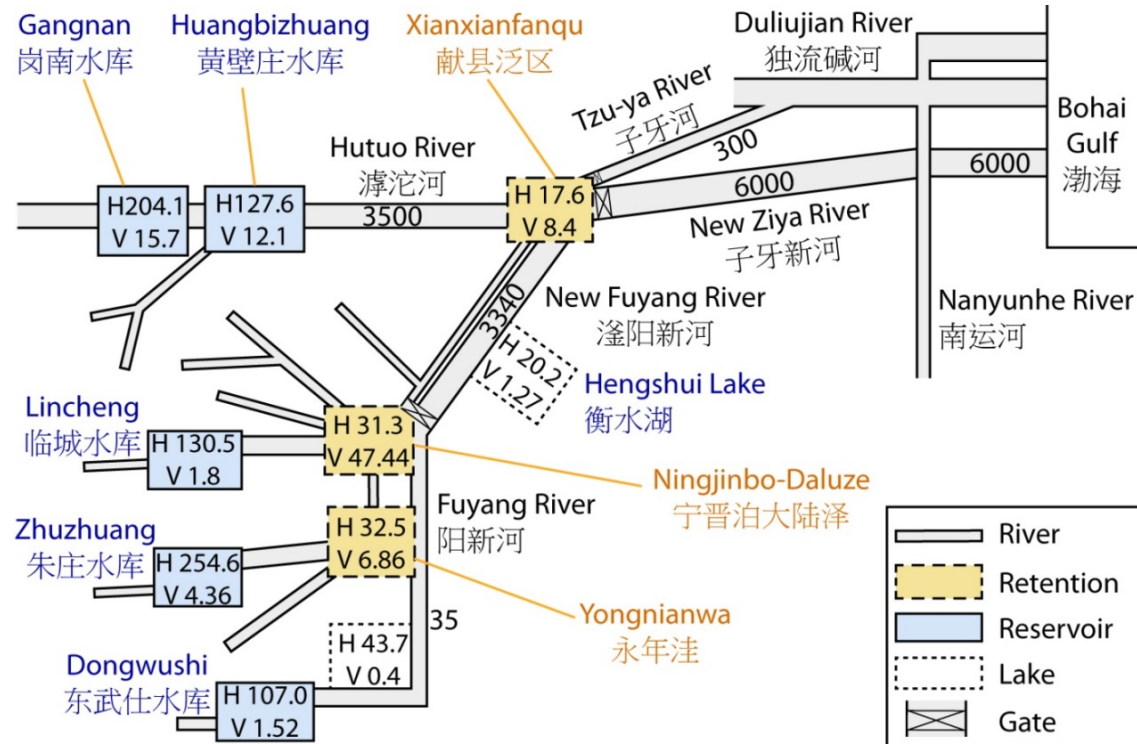


Figure 1: Conceptual sketch of the Ziya River basin based on HRWCC, (2012). Blue boxes are reservoirs, H is the hydraulic head (m.a.m.s.l.), V is the storage capacity in 10^8 m^3 . The flow capacities (m^3/s) of the main rivers are indicated. The dashed orange boxes are flood retention basins to be used as temporary storage during extreme floods, while the dashed white boxes are (probably) lakes detached from the flood protection system (Hengshui Lake and Shuinianzhu lake). The Tzu-ya River does not currently receive any water from the Ziya River, as the inlet has been closed with a dike.

Between Lincheng and Hengshui, the natural depression Ningjinbo can be used as a temporary retention basin with a capacity of 4744 million m^3 (HWCC, 2012). Similarly, the smaller Yongnianwa depression close to Handan can be used as temporary storage of 686 million m^3 . Finally, the Xiàxiàn Fànqū retention area at the junction of Hutuo and Fuyang River can store another 840 million m^3 . The New Ziya River spillway from the junction to the Bohai Gulf can carry up to 6000 m^3/s (HWCC, 2012). See photo 3g of the spillway.

In Figure 2 an overview map of the entire Ziya River basin can be seen. At the confluence point of Hutuo and Fuyang Rivers it was earlier possible to divert water into the Tzu-ya River which flows to the Duliujian River in Tianjin as illustrated in Figure 1. However, this inlet point has been closed with a dike, probably because Tianjin now receives sufficient water from the south-north carrier. This river is therefore not shown in Figure 2.

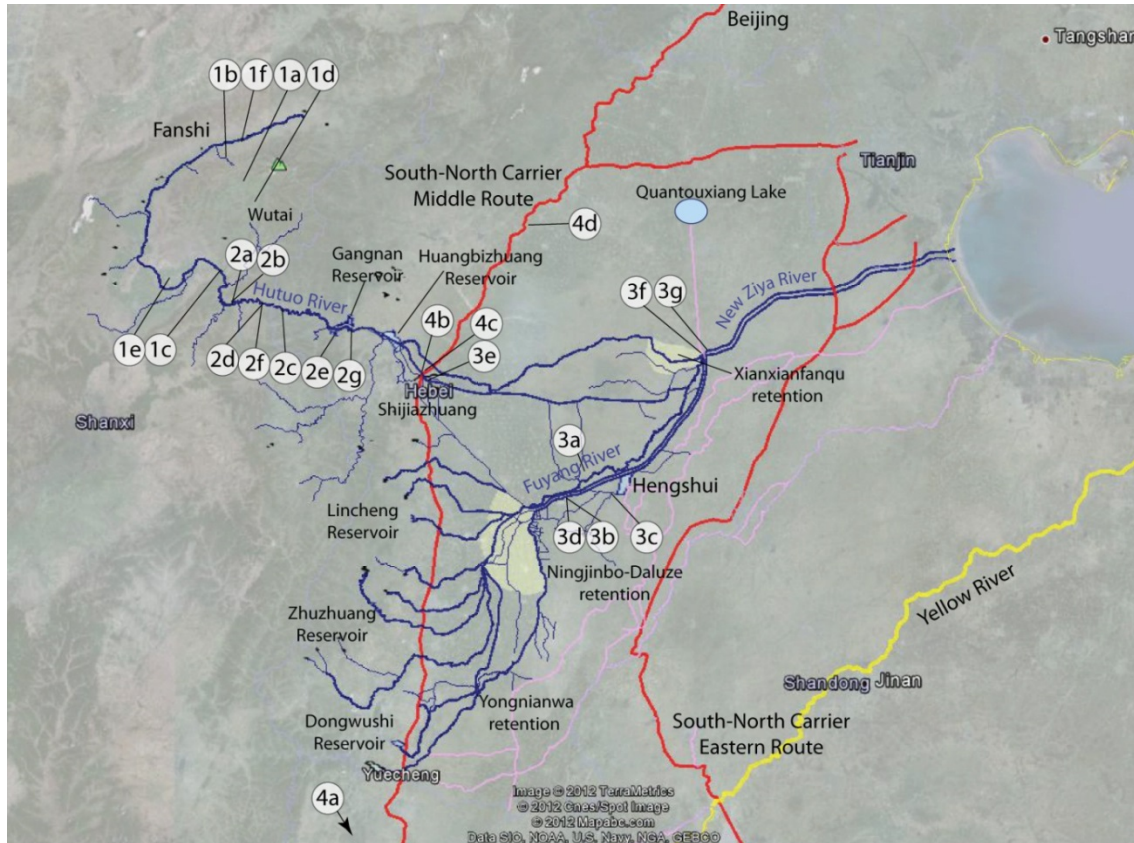


Figure 2: Overview of Ziya River basin based on (Daxixianpipi, 2011; Google Inc., 2013; HWCC, 2012), automatic watershed delineation based on SRTM imagery and manual digitalization in Google Earth. The white circles show locations of the photos in Photos (1) – (4) in the end of this field report. The red lines are the South-North Transfer project routes, the pink lines are rivers outside the basin, and the yellow line is the Yellow River. Finally, the 2 white areas show the flood retention areas. Background map: Google Inc., (2013).

3 Hutuo River

3.1 Upstream of Hutuo River

The Hutuo River was originally formed by a number of small mountain rivers flowing into the more than 10 km wide upstream delta in the Shanxi Province. Today, some of these mountain streams are cut off by reservoirs with low or no release to the Hutuo River. This reserves the water for irrigation use in the dry season but leaves the actual Hutuo River bed dry. An example can be found about 5 kilometres upstream Fanshi, where the Xiaruyue Reservoir seems to cut the Hutuo River completely (photo 1f). The river channel is covered with vegetation and seems to have been dry for several years. Downstream Fanshi in Niuzhancun, the city reservoir level is below the dead volume and therefore does not contribute with any water to the river either.

Between Fanshi and Niuzhancun, a tributary brought the majority of late-May discharge to the Hutuo River from the Taihang Mountains. This tributary carries water from a valley with intense mining activities and some small villages (photo 1b). At the entrance to the Hutuo River the water contained a lot of yellow sediment and most likely also some wastewater from the villages. Waste could also be observed along the river banks in one of the villages, and some pollution from this should be expected.

In the most upstream part of the tributary, a mine tailing deposit was visited (photo 1a). Similar deposits could be observed in connection with mining activities at many other places of the Taihang Mountains. After sedimentation, the water seemed to be reused in the mine.

In the area around Xinzhou the river was slowly flowing through a landscape dominated by maize culture with a few fields of vegetables here and there (photo 1e). Also greenhouses seemed to be commonly used for vegetables and fruits, e.g. water melon. A significant share of the fields was covered with plastic, in an attempt to reduce the evaporation from the fields (photo 1d).

3.2 Crossing of the Taihang Mountains

At the entrance point of the Taihang Mountains the Hutuo River was heavily affected by upstream water users (photo 1c and 2b). The water carried a significant amount of sediment (visibility less than 10cm), and black mud was observed along the banks indicating anaerobic conditions.

The Hutuo River crosses the mountains in a relatively steep gorge with a mixture of short vegetation, trees and bare rock. Nearby the number of small villages, some farmland was observed (example shown in photo 2d). Wheat could still be observed, but mixed vegetables seemed to dominate the fields. As a consequence of the steep gorge, many gravity-driven irrigation diversions were observed close to the villages. A few of these channels were able to carry a significant part of the present flow. The flow was estimated to be no more than a few m^3/s .

The sediment content seemed to be reduced as the river crossed the mountains. This can be explained by a low flow velocity in some stretches. Especially around a small wetland area (photo 2c), the river was wide and without visible current for a few kilometres.

Small dams with diversions to hydropower stations and irrigation were observed in the mountains, leaving the Hutuo River dry or with negligible flow for a few kilometres here and there (see photo 2a). This part of the basin is also home for intense mining activities with dedicated railways carrying material away from the mines. Also many trucks (something like 1 every 2 minutes) are carrying grey stones away from the mountains (photo 2f). The Shanxi Province is known for its large coal and aluminium resources, but at this point it is a bit unclear which resources can be found in this part of the Taihang Mountains.

After the mountains the Hutuo River flows into the Gangnan Reservoir. The reservoir level was estimated 20 m below the normal storage based on the vegetation along the lake (photo 2e). The low water table enabled a large area to be used for agriculture.

At the Gangnan Dam, the water was clear and odourless. There is public access to the lake from a parking lot at the dam, and local people swimming in the reservoir could be observed. The site looked a bit like a small beach park (photo 2g). In contrast it was a bit more difficult to access the water at the Huangbizhuang Dam, but a group on bicycles and a number of fishermen revealed that also this area provides the locals with ecosystem services.

3.3 Shijiazhuang

Water released from the Huangbizhuang Reservoir flows in the new Hutuo channel (the original river bed is dry). Less than 2 km upstream the long city lake in Shijiazhuang, the channel crosses the South-North carrier (see Figure 3 and photo 4b). At this point, water can be diverted from the Hutuo River

into the carrier and eventually to Beijing and Tianjin. According to the local management engineer situated at the inlet point from the Hutuo River in Shijiazhuang, 10.35 m³/s of water was diverted into the carrier at this day in end-May. The day before, we crossed the carrier next to the city Tangxian, approximately 150 km southwest of Beijing. The flow velocity at this point was estimated to be a few centimetres per second.

It is at this point unknown if the planned diversion from the carrier to Tianjin is already in use. This will divert water from a point between Tangxian and Beijing. The connection from Yangtze River was still under construction and will involve a tunnel under the city lake as shown in Figure 3.

2 km downstream the carrier junction, the Hutuo River channel crosses the Shijiazhuang city lake (photo 3e) in a tunnel. At this point a control structures with several gates make it possible to divert water into the city lake or to the New Hutuo River making the water available for irrigation. This is a very clear example of conflicting water uses.



Figure 3: Overview of the South-to-North Transfer Project junction with Hutuo River in Shijiazhuang. Background map from Google Inc., (2013).

4 Fuyang River

The Fuyang River basin is shown in Figure 4. Water from the Taihang Mountains is captured by a number of reservoirs before it enters the NCP. The River Commission operates with only 3 reservoirs in their main model (according to their principle sketch); the Lincheng, Zhuzhuang and Dongwushi reservoirs. In reality around 20 tributaries transport water from multiple reservoirs in the Taihang Mountains to the Fuyang River.

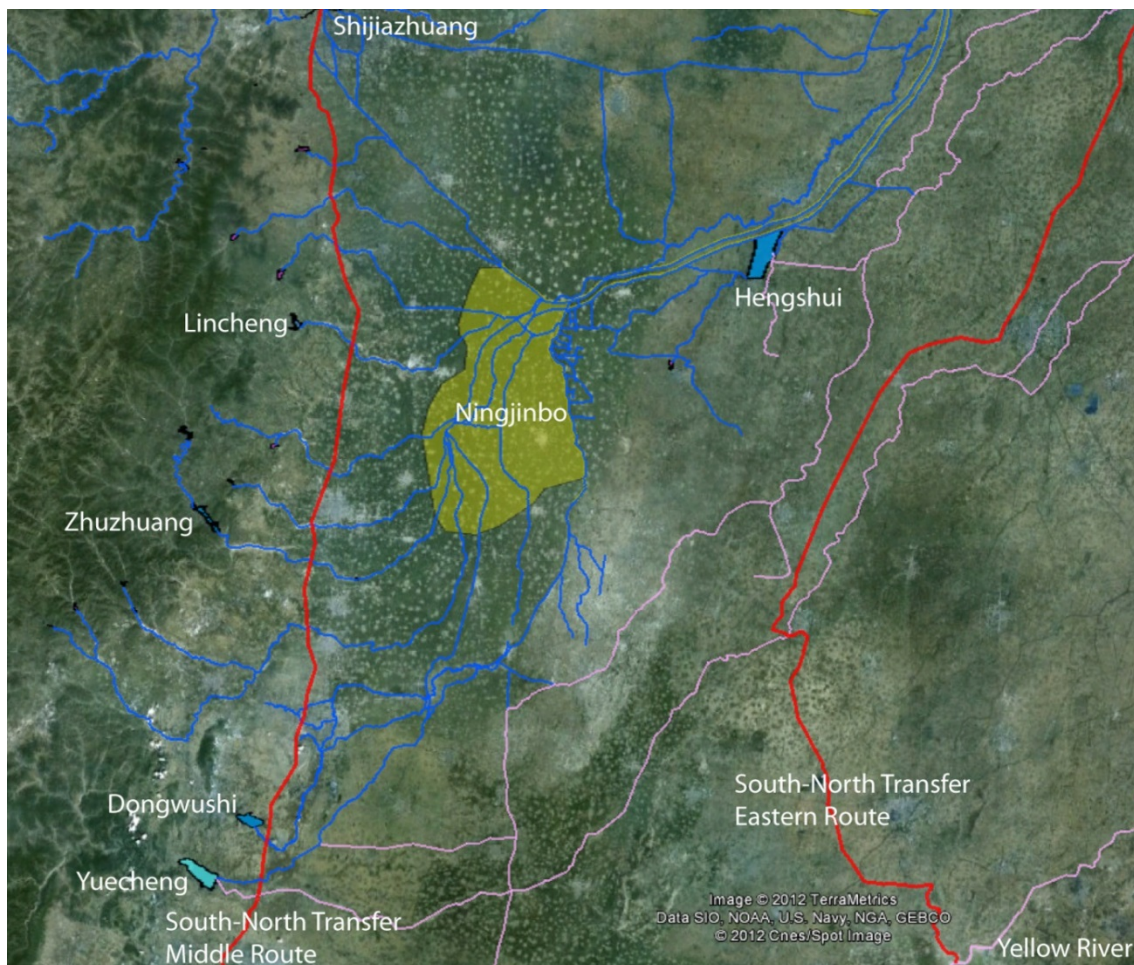


Figure 4: Overview of the Fuyang River system, including also some rivers outside the basin (pink) and the South-North water transfer channels (red). The Ningjinbo temporary flood storage is indicated with yellow. Water from the mountains is collected in a number of reservoirs, including the 4 main reservoirs Lincheng, Zhuzhuang, Dongwushi and Yuecheng. From here the water flows into a complex network of rivers and channels and non-used water enters the New Fuyang River which eventually joins the Hutuo River. Background map from Google Inc., (2013).

The New Fuyang River and the original Fuyang River flow parallel to the junction with Hutuo River. South of these channels, another channel carries water what seems to be from the Yuecheng reservoir. This channel crosses the Ziya River at the junction point (photo 3f) and flows to the wetland area of Quantouxian Lake. This channel carries cleaner water than the Fuyang and Ziya Rivers which have characteristics of wastewater. Earlier, water could be diverted to the north from the Fuyang-Hutuo junction, but this channel is now blocked with a dike and all water flows directly to the Bohai Gulf.

The intensive farming in the area is highly dependent on irrigation water. An extensive system of groundwater pumps (photo 3a) supplies the majority of the irrigation water. Most of the area is used for a 2-crop system with irrigated winter wheat and rain fed summer maize. The farmers seem to use mainly furrow irrigation. Surface water is used on farmland close to irrigation channels (photo 3c)

Next to the New Fuyang River, south-west of the Hengshui Lake, a local farmer explained some of the common agricultural practises. Private companies travel around by the time of harvest and negotiate the producer's price of the crops. Once an agreement has been made, another company will be hired in to harvest the crops, using machines. The farmer had a small tractor and a plough and can thereby also use machines for the cultivation work. From observation in the landscape it was clear that many farmers applied pesticides on the crops, using manual hand pump systems.

The farmer also explained how the irrigation water from Fuyang River (3d) has increased the number of cancer incidents in the village. They are aware that the water contains toxic compounds (most likely industrial wastewater), and they avoid eating their own crops. Instead they buy crops on the market.

The Hengshui Lake has previously been fed by the Fuyang River, but water scarcity and water pollution has increasingly put a pressure on the ecosystems of the lake. A project diverting water from the Yellow River has therefore been carried out and the Yellow River water can now be diverted into Hengshui Lake (Hengshui City Water Authority, 2011). The water table has been increased with 1.6 meters and already improved the ecosystem. The lake is an important habitat for many bird species and an important source of drinking water for Hengshui.

5 New Ziya River and the confluence point

The Hutuo River and Fuyang River confluences close to the village Xianxian and forms the New Ziya River as shown in Figure 5. The New Hutuo River, which brings water to the South-North carrier and crosses the city lake in Shijiazhuang, flows into the original Fuyang River at point **a** on Figure 5. At point **b** this river flows into the New Fuyang River channel, which again 2 km further downstream confluences with the Hutuo River at point **c**. From here the black water flows directly to the Bohai Gulf in the New Ziya Spillway. The water has wastewater characteristics, and in May the discharge was very low (not more than a few m³/s). Earlier, water from the Ziya River could be diverted to Tianjin, which is still indicated on the River Commission water balance (Figure 1), but on site it could be seen that this channel has now been cut with a dike.

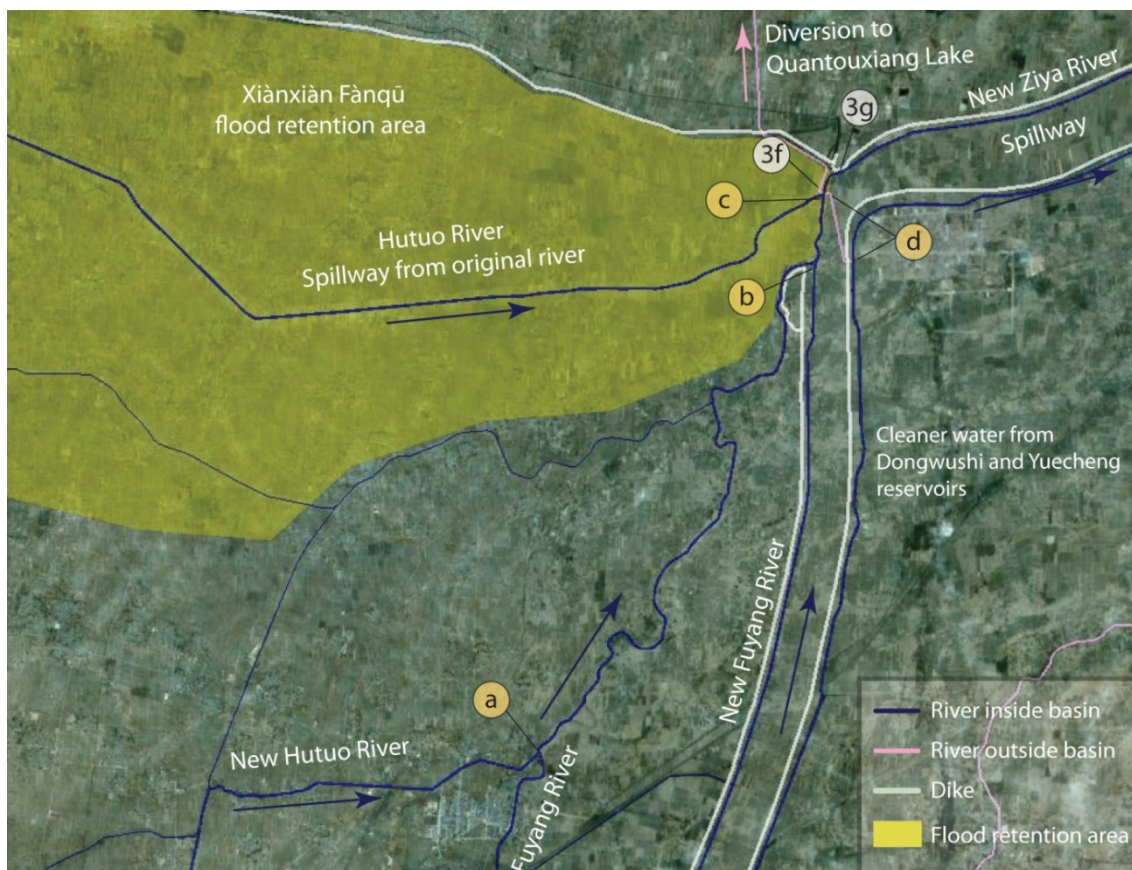


Figure 5: Confluence of Hutuo and Fuyang Rivers. The white circles indicate photo locations and the orange circles are as follows: a) confluence of the New Hutuo River and the old Fuyang River; b) confluence of the old and New Fuyang rivers; c) confluence of the old Hutuo River and the Fuyang River; d) diversion of water to the Quantouxiang Lake from the channel south of the New Fuyang River. This channel carries clean water from the Dongwushi and Yuecheng reservoirs and crosses under the New Ziya River.

The channel south of the Fuyang River carries water from the Dongwushi and Yuecheng reservoirs. At point **d** water is diverted from this channel, under the dike, across the spillway, under the Ziya River, (photo 3f), under the second dike and into a new channel to the Quantouxian Lake. This water seems to be cleaner than the water flowing in the Hutuo and Fuyang Rivers.

6 Meeting with the Hai River Water Conservancy Commission

6.1 Participants

Dan Rosbjerg, Suxia Liu, Peter Bauer-Gottwein, Claus Davidsen

From the Hai He River Water Conservancy Commission (from now: the River Commission): Division Director **Han Ruiguang** (Science Technology and Foreign Affairs Division), Deputy Director **Mei Chuanshu** (Science Technology and Foreign Affairs Division), Deputy Director **Yan Zhanyou** (Water Policy and Water Resources Division), Chief Engineer **Wang Jiangang** (Office of Flood Control and Drought Relief), Senior Engineer **Wang Liming** (Water Resources Protection Bureau), Senior Engineer **Wen Licheng** (Bureau of Hydrology), Deputy Director **Zhang Jianzhong** (Consultative Center of Science and Technology), Deputy Director **Song Qiubo** (Zhongshui Water Science and Technology Consultation Co. Ltd.), Deputy Director **Yu Lei** (Lonwin Science & Technology Development Co. Ltd.).

6.2 The Haihe River basin

There is high focus on the Haihe River basin as this 320,000 km² basin is important both in an economic and political perspective. 8 provinces and 140 million people need to share the scarce water resources of the Haihe River, and the role of the River Commission is to divide the water resources between the provinces. Key data for the Hai River basin is presented in Table 1.

Ziya River basin is the part of Haihe River with the least water available per inhabitant. The basin has an area of 46,868 km² with 66.4% being mountainous areas. These mountains receive in average 600 mm precipitation per year, whereas the downstream area on the North China Plain (NCP) receives in average 400 mm/year. Beside the low annual precipitation, there are also several other problems associated with the precipitation in the Haihe River basin.

80% of the precipitation occurs from June-September, and the annual variations are therefore extreme. Further, the inter-annual variations are also significant with a typical span from 200 to 1000 mm/year. In the Ziya River basin, the historic precipitation measurements show variations between 271 and 2594 mm/year.

Table 1: Average Hai River data

Hai River Basin	Annual average (10^8 m^3)
Annual recharge	370
Surface water runoff	216
Flood storage capacity	173
Actual supply since 1980	390
Total allocations to agriculture	279
<i>Irrigation agriculture</i>	255
<i>Forests and aquaculture</i>	24

The area experience flood events every 2.5 years and extreme floods occur every 17 years. Major floods occurred in 1963 and 1996. In 1963 record breaking 2050 mm precipitation was measured in a 7-day period in the Ziya basin. The risks of the floods are further increased by a very short travel time from the mountains to the NCP. The mountains are very steep and it takes only 4 hours for the water to reach the NCP.

Since 1949 a lot of focus has been put on flood control of the Haihe system. There is a total of 9000 km of dikes in the Haihe basin, and the 1,823 reservoirs have a combined capacity of $320 \cdot 10^8 \text{ m}^3$. The Fuyang and Hutuo Rivers are both controlled by multiple reservoirs, which can cut the peak discharge. Further, the New Ziya River spillway to the Bohai Gulf enables fast discharge of water.

The $255 \cdot 10^8 \text{ m}^3$ irrigation water is used for the winter wheat and in some years in the beginning of the summer for maize. Cotton, rice and vegetables are grown at smaller scale. 70-80% of the agricultural demands are satisfied with groundwater. The basin has 1.36 million groundwater wells.

6.3 The Gangnan and Huangbizhuang reservoirs

With a combined capacity of $27.8 \cdot 10^8 \text{ m}^3$ (HWCC, 2012) the Gangnan and Huangbizhuang reservoirs can store an inflow larger than the average annual inflow and are only filled up during flood events. This enables inter-annual storage of water. The reservoirs provide Shijiazhuang with water for domestic, industrial and ecosystem uses and supply the downstream areas with irrigation water. Approximately $1 \cdot 10^8 \text{ m}^3$ is allocated to domestic users and $0.61 \cdot 10^8 \text{ m}^3$ is allocated to ecosystems.

The total water use in China are expected to increase from $6315 \cdot 10^8 \text{ m}^3$ in 2015 to 6700 and $7000 \cdot 10^8 \text{ m}^3$ in year 2020 and 2030 respectively. The South-North Water Transfer project was approved in 2002 and is now linking the Hutuo and main Fuyang reservoirs with Beijing and Tianjin. The canal will soon be connected with the Yangtze River and transfer $9.5 \cdot 10^9 \text{ m}^3/\text{year}$ (water-technology.net, 2013). This will increase the water available for allocations in the NCP and help to decrease the groundwater pumping.

6.4 Future management and policies

The Chinese Government has increasingly focus on water resources management and introduced recently a central red line rule with 3 key focus areas; efficiency, development and pollution. As a consequence, a set of 2030 goals have been developed for the Haihe River basin. The total water use should not exceed $500 \cdot 10^8 \text{ m}^3$ and a maximum of 75% should be used for agriculture (irrigation use coefficient). Further, 95% of the water areas should comply with the water quality standard of the area. Each area, e.g. a part of a river, has been classified into a function class, e.g. ecological protection. As it was observed in the basin, different rivers with different water qualities are therefore kept strictly isolated from each other in a quite complex system.

The River Commission is in particular interested in models, which can help evaluate future projects (e.g. new reservoirs). Also, the River Commission suggested that future projects could strongly improve by building on experiences from previous projects (GEF, UNDP) and the Chinese Governments water resources assessment report. Most reports are, however, only available for internal use in the Governmental bodies and thereby not accessible for the public (or researchers).

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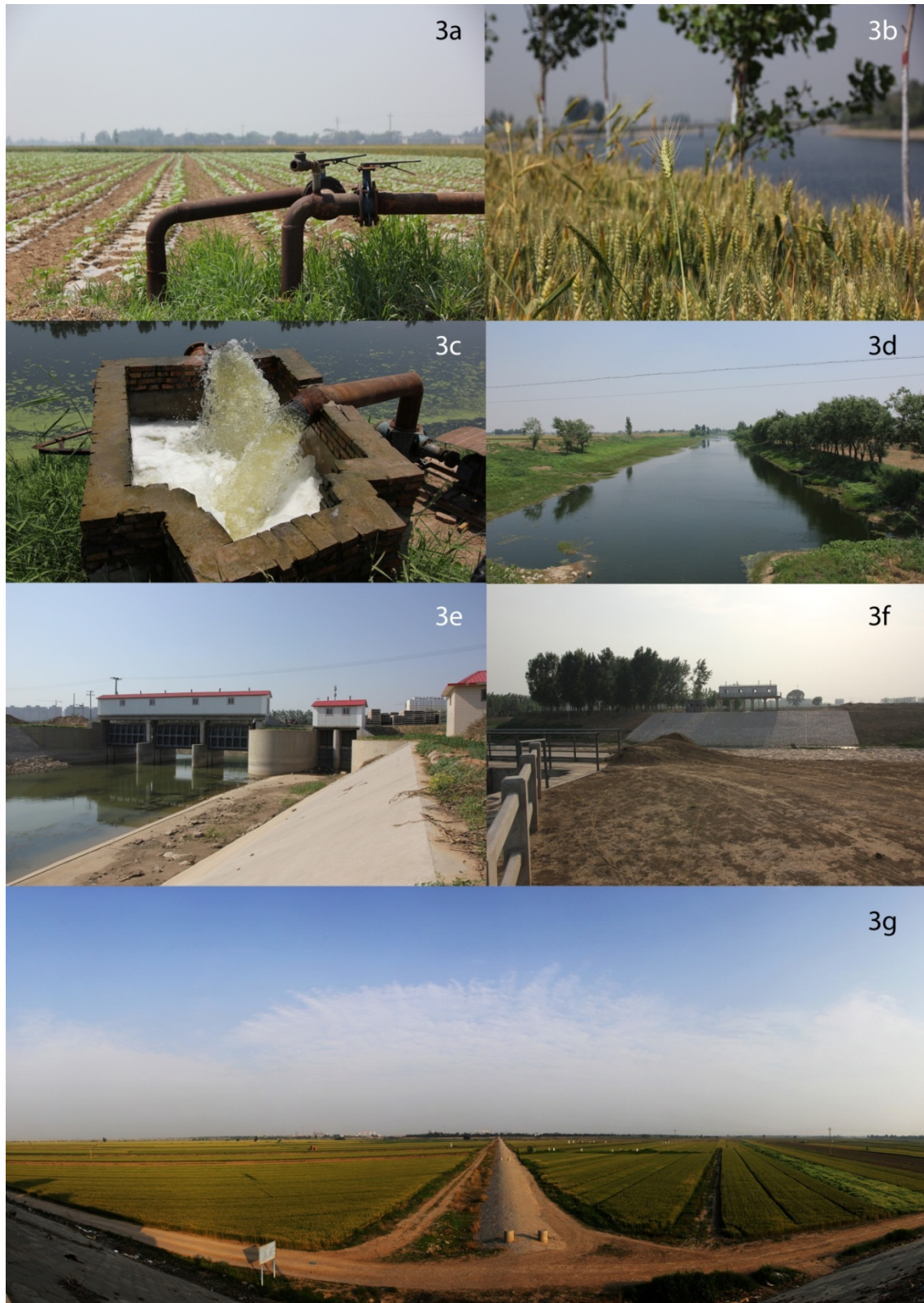
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Photos (1): Shanxi Province. 1a) head water sedimentation basin, 1b) tributary to Hutuo River, 1c) Hutuo River downstream Xinzhou, 1d) ET reduction farming, 1e) farmer at maize field, 1f) Xiaruye Reservoir



Photos (2): Crossing the Taihang Mountains. 2a) Hydropower diversion, 2b) black anoxic sediment, 2c) small wetland area, 2d) farming on the river bed, 2e) upper Huangbizhuang, 2f) mining trucks, 2g) Huangbizhuang reservoir dam



Photos (3): North China Plain. 3a) groundwater pumping station, 3b) wheat 2 weeks from harvest, 3c) surface water pumping station, 3d) New Fuyang River channel, 3e) diversion station in Shijiazhuang, 3f) channel to Baoding crossing Ziya River, 3g) the Ziya River spillway to the Bohai Gulf



Photos (4): South-North Water Transfer Project. 4a) Construction of channel south of the Yellow River crossing, 4b) inlet from the Hutuo River, 4c) Crossing of the New Hutuo River channel, 4d) the finished carrier in operation



Field Report 2, July 2012

Claus Davidsen

Field Report 2, July 2012

Author: Claus Davidsen



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1 Introduction

On 15-18 July, 2012 the Ziya River basin was re-visited. The field trip team was:

- Claus Davidsen, PhD student, DTU Environment and CAS IGSNRR
- Sidsel Hansen, MSc student, DTU Environment
- Victor, English-speaking Chinese driver

The field report describes the main findings of this second field trip and provides an updated introduction to the current management practises. Whereas the first field trip mainly focused on the Hutuo River and the northern Fuyang River, this second trip focused mainly on the Fuyang River in the southern part of the basin. This report will therefore give an introduction to:

- The reservoirs that release water into the Fuyang River
- Current water management practices of the Fuyang River
- Water quality of Fuyang River
- Pollution sources of Fuyang River

In Figure 1, a modified version of the conceptual sketch from the first field report can be seen. New features include the Yuecheng Reservoir situated a few kilometres south of the Ziya basin, a small drinking water pipe from Yuecheng to Handan and also the Fu Dongpai channel, which follows the New Fuyang River all the way to the Bohai Gulf. Finally the Baiyangdian Lake, a proposed reservoir in Shanxi and the South to North Water Transfer Project channel are now added to the sketch. The flood retention areas and the historic channel to Tianjin are for simplicity not shown.

For comparison with Figure 1, the Google Earth digitalization can be found in Figure 4.

2 Reservoirs of the Fuyang River

As mentioned in field report 1, a large number of small and medium reservoirs can be found in the Taihang Mountains on the western border of the North China Plain (NCP). The Haihe River Commission operates with the 3 main reservoirs of the Fuyang River; Lincheng, Zhuzhuang, and Dongwushi with a combined capacity of 768 million m^3 . In the following sections the field observations from each of these reservoirs will be described.

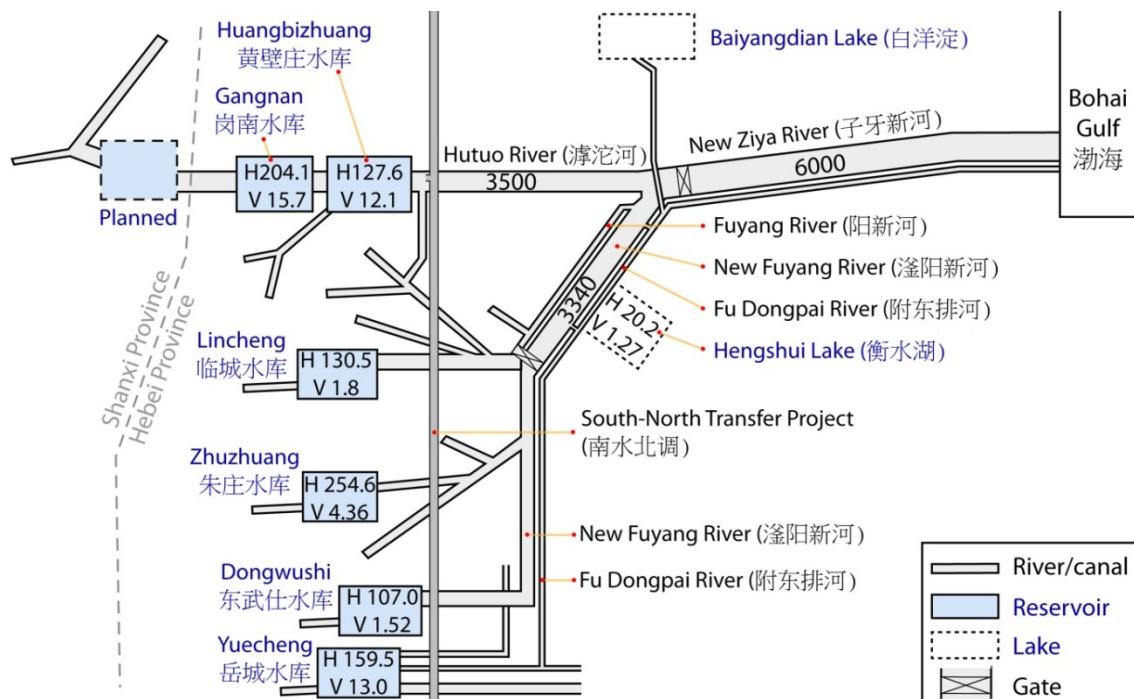


Figure 1: Conceptual sketch of the Ziya River basin based on (HWCC, 2012) and field observations. H is the maximum head (m.a.s.l.) and V is the storage volume as given by the Hai River Commission (the unit is 10^8 m^3). “V 1.0” equals a storage volume of 100 million m^3 . The flow capacities (m^3/s) of the main spillways are also indicated. The three flood retention areas and the old Tianjin channel are not shown.

2.1 Lincheng Reservoir

The Lincheng Reservoir is situated 65 km south of Shijiazhuang. The reservoir has a maximum storage capacity of 180 million m^3 and reservoir releases join the New Fuyang River 65 km downstream. At the northern end of the dam, a **tourist park** has recently been established. The park contains a variety of temples and beautiful lake sceneries (see photo collage 1). Tourists

interested in boating tours can choose between three open 50-seat tour boats or one of the smaller tour boats.

The landscape is hilly and green with the Taihang Mountains in the back. The water was not very clear (visibility of around 1 m) but was not smelly. The water level was approximately 10 m below the top of the dam, leaving some room for flood retention. However, parts of the tourist park will be flooded, if the water level is raised.

2.2 Zhuzhuang Reservoir

The Sha River carries releases from the Zhuzhuang Reservoir over a distance of 90 km to the Beili River, which subsequently flows into the New Fuyang River outside Ningjin City. The water level in the reservoir was estimated 20-30 m below the top of the dam. People were observed fishing and swimming in the reservoir. The landscape is mountainous with bare rock visible between green vegetation (see photo collage 2).

Four km downstream of the reservoir, the locals were using the Sha River for **washing their cars** and motor bikes. The water flows across the road in a 100 m wide and shallow (10-20 cm depth) section. Approximately 30 people were busy washing 4 cars (1 including the engine) and 8-10 motor bikes. The water was clear and odourless with leftover plastic and other waste from the washing activities.

The river bed from the car wash point and 15 km downstream has been extensively used for quarrying activities. The river bed looked like a moon landscape and was covered with stacks of rocks and sand.

2.3 Dongwushi Reservoir

The Dongwushi Reservoir has a maximum storage capacity of 152 million m³ and is situated 15 km north east of Yuecheng Reservoir and 30 km southwest of Handan City. The water level was around 5 m below the top of the dam at the time of visit. The reservoir is used for **extensive aquaculture** and is covered with cages of fish nets (see photo collage 3). Between these fish farms the fishermen have established water roads for their boats. A fisherman was observed feeding the fish by throwing the content of sacks into the cages.

The Fuyang River is formed by releases from the Dongwushi Reservoir, and a flow of a few m³/s was observed in the village Donghuaishucun, 5 km downstream of the reservoir. Whereas the reservoir water was clear with some algae growth and a smell of fish, the Fuyang River was white as milk

with a visibility of a few centimetres. It is yet unknown if this white colour is caused by sinking fish food, algae formation or an external source between the dam and the river crossing. From Google Earth (Google Inc., 2013) no inlets can be found, but perhaps some industry releases wastewater to the river. The area is rich on minerals (e.g. limestone and chalk) and multiple cement industries were found in the area around Handan. Finally, the area is also rich on iron, and calcium carbonate is used in the purification process of the iron ore. According to Trapp (2012), an explanation could therefore be that the river is oversaturated with calcium carbonate, which would cause this grey/white colour of the water.

2.4 Yuecheng Reservoir

The Yuecheng Reservoir is situated 45 km southwest of Handan city, which has a population of 1.4 million people. Yuecheng Reservoir drains into the Zhang River, which is not a part of the Ziya River basin. However, the reservoir is still important as **underground pipes supply Handan** daily with 200,000 m³ water for domestic and industrial purposes. Further, an irrigation channel being fed directly from the reservoir can transport water into what eventually becomes the Fu Dongpai River (flows parallel to the New Fuyang River).

The reservoir water level was low and the 9 gigantic spillway gates with a total capacity of 12,820 m³/s were a few meters above the water table. The water table was estimated 15 m below the top of the dam. The big gates have not been in use since the last major flood in 1996, which has allowed trees to grow right below the spillway.

People were observed fishing and swimming in the reservoir, and it was possible to buy boat trips in one of the 8 boats present on site.

3 South-to-North Water Transfer Project

The South-North Water Transfer carrier crosses the Yellow River between Luoyang and Zhengzhou and follows the eastern side of the Taihang Mountains up to Shijiazhuang. Both the Lincheng, Zhuzhuang, Dongwushi and Yuecheng reservoirs are all situated a bit upstream from the carrier. Reservoir releases will cross under the South-North carrier with no possibility of diverting water into the carrier. Water from the Fuyang basin can therefore not be allocated to Beijing and Tianjin through the carrier.

Intense construction work was on-going on all the observed parts of the carrier south of Shijiazhuang. The construction work includes many large road bridges, levelling of the landscape and tunnels at river crossings.

23 km north of Baoding some of the water in the carrier can be diverted into a 150 km long new closed channel to Tianjin. Construction of this pipe is still on-going and includes an open basin for what could be a small drinking water reservoir for the local villages or perhaps a buffer for Tianjin (see photo collage 4).

4 Taihang Mountains

The Taihang Mountains between the Lincheng and Dongwushi Reservoirs were visited. From Lincheng Reservoir to Zhuzhuang Reservoir the roads S327, S202 and S321 were used as a detour into the Taihang Mountains. This part of the mountains reaches up to 1500 m.a.s.l. and is very green and fertile. The valleys are used for growing primarily maize and mixed vegetables (see photo collage 1, photo 1d). A farmer explained that the local community shares the harvest of maize, which is used mostly to feed the animals. The farmer had his own groundwater well to supply him with drinking water and owned 0.8 hectares of non-irrigated farmland. Some small rivers were crossed in the mountains, but none of them were carrying more than a few m³/s each.

5 Fu Rivers at the North China Plain

Fu Dongpai River is an eastern parallel canal to the New Fuyang River. This canal originates as an irrigation diversion from Yuecheng Reservoir and runs outside of New Fuyang River spillway eastern dike and, downstream of the confluence, on the southern side of New Ziya River dike (see Figure 1).

Fu Dongpai River and New Fuyang River are connected by cross channels at several points, allowing water to be diverted from channel to channel. Such a diversion was observed from the New Fuyang River to Fu Dongpai River at the beginning of the Fuyang spillway. Upstream this point there was only stagnant water in the Fu Dongpai River, so the estimated 10-20 m³ of wastewater flowing in from New Fuyang River made a significant contribution to the river flow (see photo collage 5).

The word wastewater is used for the channel water, as this black water with white foam and a very strong smell of chemicals and slurry showed no similarities with the mountainous water observed further upstream in the system. While crossing a flood gate, the wastewater dropped a bit causing turbulent flow. Perhaps, this water was untreated domestic wastewater from the upstream cities. A 5 minute exposure to the strong smell resulted in smelly in clothes and headache for a few hours.

At the same time 5 km downstream, estimated 10 cm/s upstream moving flow could be observed in New Fuyang and Fuyang rivers. This flow was probably caused by the water diversion to Fu Dongpai River.

In Hengshui the Fu Dongpai River receives any outlet from the Hengshui Lake. Hengshui is located only 50 km from the wastewater diversion point, and it was therefore surprising to see people fishing in the water. The water level in the river was at least 1 m below Hengshui Lake and the river was widely covered with a green layer of duckweed. The water was dark black and a bit clearer than the wastewater diverted to the river.

5.1 Hengshui Lake

As a consequence of the scarce and heavily polluted water resources of the Fuyang River, the original south-western inlet to Hengshui Lake from Fuyang has been closed by dikes (see field report 1). Instead, Hengshui Lake has in the recent years been supplied with water from the Yellow River. A local man explained how water once a year enters the lake through the eastern flood gate. Existing rivers, e.g. the Qingliangdiang River (清凉江) 22 km east of the Hengshui Lake, are primarily used to carry the Yellow River water.

Local people in Xianxian village mentioned large paper industry in Hengshui city. Accordingly, green water is flushed into the river (probably Fuyang River) during rainfalls. They explained that people are scared of the potential toxic chemicals and the consequences for people and the Bohai Gulf.

5.2 The confluence point

Fuyang River and New Fuyang River confluences outside Xianxian village as also described in the first field report. This river and Hutuo River join 2 km downstream and form the New Ziya River (see Figure 2). As shown in Figure 2, multiple gates make it possible to move water freely between the rivers. At the time of visit, gate #a was closed and #b open, which allowed water to flow from Fu Dongpai to the Ziya River. A flow of less than 1 m³/s could be

observed, which is much less than the quantity entering Fu Dongpai 125 km upstream. The waste water was probably diverted back to New Fuyang River using another cross channel or used for irrigation.

The gates at #d were earlier used for diverting water to Tianjin. Tianjin now receives clean water from the South-North carrier and has refused to receive the polluted Ziya water. The flood gate e# at Ziya River was wide open and a flow similar to the cross canal input to Fu Dongpai was observed (see photo collage 6, photo 6c). The water had same colour and smell as the observed water diverted into the Fu Dongpai River.

A couple of hundred meters downstream the flood gate #c a group of children were observed swimming in the Baiyangdian canal. Only stagnant water was present in the canal at this time. The water was relatively clear and odourless.

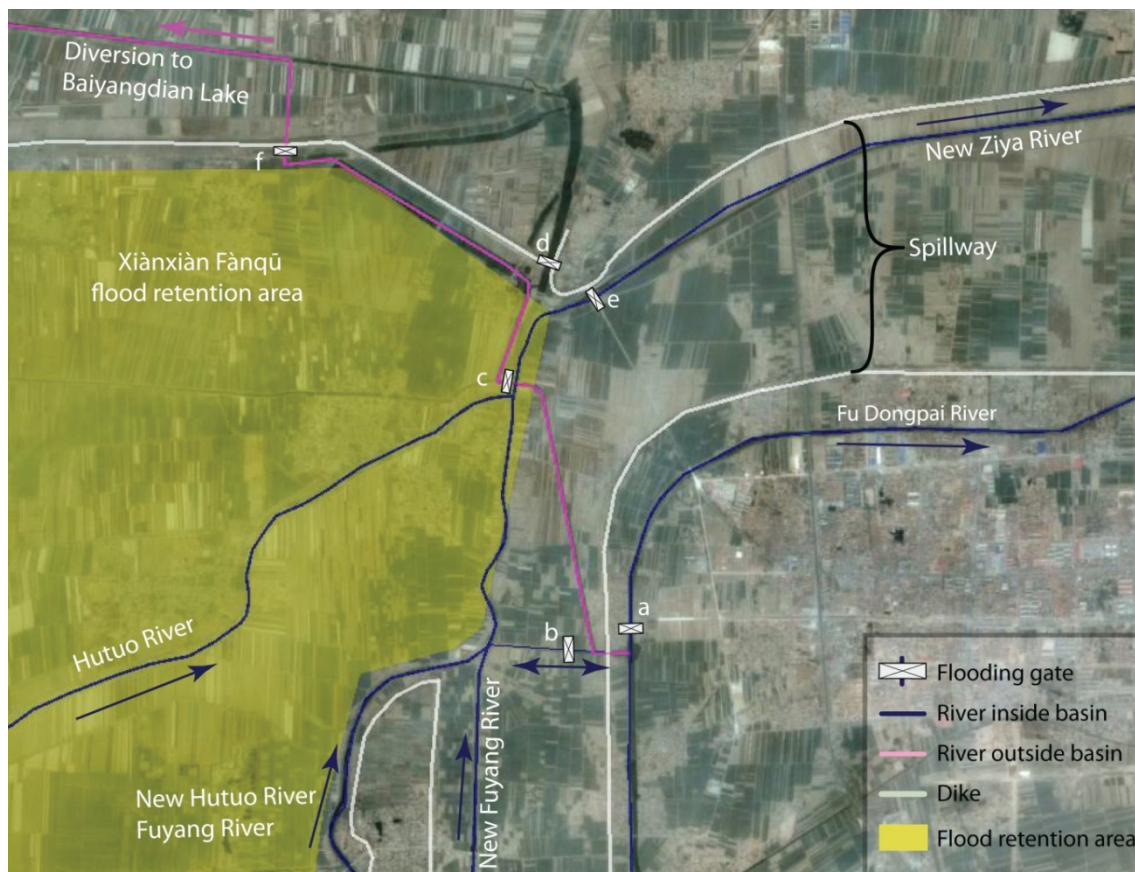


Figure 2: Confluence of Hutuo and Fuyang Rivers at the Xianxian village. A cross canal can move water between the Fu Dongpai River and the confluence point of Fuyang River/New Hutuo River and the New Fuyang River. Multiple flood gates (a-f) enable control of how water moves between the rivers. Background map from Google Inc., (2013).

5.3 Fu Dongpai diversion to Baiyangdian Lake

In Figure 2 the pink line shows the canal from Fu Dongpai River to Baiyangdian Lake. Old rivers are used to carry the water most of the way to the lake. A part of the way the water flows in the Xiaobai River, which crosses highway S381 in the small village Chu'anzen. Here a local man explained that guaranteed clean water will be diverted to Baiyangdian Lake 2 times every year (see photo collage 5, photo 5d).

Knowing the present pollution level of Fu Dongpai River, there will surely be challenges to guarantee clean water, but before the inlet point to Baiyangdian it seems to be possible to divert water directly to the Bohai Gulf. A guess is that the managers can flush all the wastewater out of the system and, whenever the water is clean enough, divert to Baiyangdian Lake.

5.4 Connection between Hutuo-Fuyang Rivers

A channel from Shijiazhuang connects to a tributary of the Fuyang River basin. This channel was visited in the southern suburbs of Shijiazhuang and was carrying a few m^3/s . The capacity of this channel was estimated to be in the same range of the South-North carrier, which thereby enable significant water transfer from the Huangbizhuang and Gangnan reservoirs in the Hutuo River system to a large part of Fuyang. The water was of medium quality.

6 Ecosystem services

At the two field trips it has been observed that the rivers, reservoirs and lakes provide a variety of ecosystem services, including fishing, aquaculture, swimming, lotus flower production and boating tours. In Handan city the Fuyang River provides water for two parks with a total area of 0.7 km^2 . The parks include a few lakes, which are used for fishing and to create some beautiful scenery in the urban area (see photo collage 6, photo 6b).

20 kilometres north-east of Handan the ancient city Guangfuzhen also enjoys access to surface water resources. The city is surrounded by a big city wall and a moat (collage 6, photo 6d). The city is an emerging tourist site providing an authentic look into the old building style of ancient China. With the current trend of extensive restoration projects, Guangfuzhen offers a rarely seen look into old China. Flushing toilets have not yet found their way into the city, and this helps to protect the surrounding water resources. The moats surrounding the city seemed clean and did not smell. A large number small

lakes or ponds are situated around Guangfuzhen. These are used for aquaculture and provide the city with fresh supplies of fish.

7 Ziya River basin border

The North China Plain is very flat, and due to the many man made channels it is difficult to differentiate original river basins from each other. It requires a good understanding of the current management of the canals to make the qualified assumptions needed for drawing a basin border.

MWR. Bureau of Hydrology (2011), which collect publish the annual river discharge books, uses a Ziya River Basin border, which follows the Zhang River from the Yuecheng reservoir. This catchment therefore includes the Fu Dongpai River, the Hengshui Lake and a number of smaller rivers discharging directly into the Bohai Gulf (see Figure 3).



Figure 3: The Ziya River basin as found in the Chinese Hydrology Bureau river yearbooks (MWR. Bureau of Hydrology, 2011). The blue line shows the border commonly used by the Chinese Academy of Sciences, Institute of Geographic Sciences and Natural Resources Research, whereas the green border shows the draft catchment border for this PhD study. The orange line shows a possible extension to include the Baiyangdian Lake

Previous and on-going research on the CAS Institute of Geographic Sciences and Natural Resources Research has used a catchment cropping away both Hengshui lake, Fu Dongpai and the Ziya Spillway (see blue line on Figure 3). While this can be okay for research focusing on crop growth, it is not really suitable in a water management perspective. Field observations showed that water is moved from the Fuyang River to the Fu Dongpai River and similarly water from both Yuecheng Reservoir and Hengshui Lake can enter the Fuyang River.

As this project focuses on the Fuyang and Hutuo Rivers, it might not be suitable to use the basin border from the Chinese Hydrology Bureau. The small rivers southeast of Hengshui are not directly linked to any of the main rivers in the Ziya River basin and are therefore not relevant in a management perspective. Same arguments apply for including the Fu Dongpai River, partly the Yuecheng Reservoir and the Hengshui Lake. They are contributing to flow in the New Fuyang River and should therefore be included in future optimization work. The green line on Figure 3 shows the draft basin border based on the above arguments.

The orange line on Figure 3 shows some additional areas, which can be supplied by water from the Ziya River basin. North of Shijiazhuang, water can be diverted from the South-North carrier into a river going to Baiyangdian Lake. Thereby Baiyangdian Lake can receive water from both the Hutuo and Fuyang rivers. A fair assumption will be to make a super reservoir and then supply the NCP-part of the basin with this water. Tianjin, Beijing and Baiyangdian will then receive water based on constraints or marginal benefits.

On the next pages, four photo collages can be found. Figure 4 show the locations of the many photos.

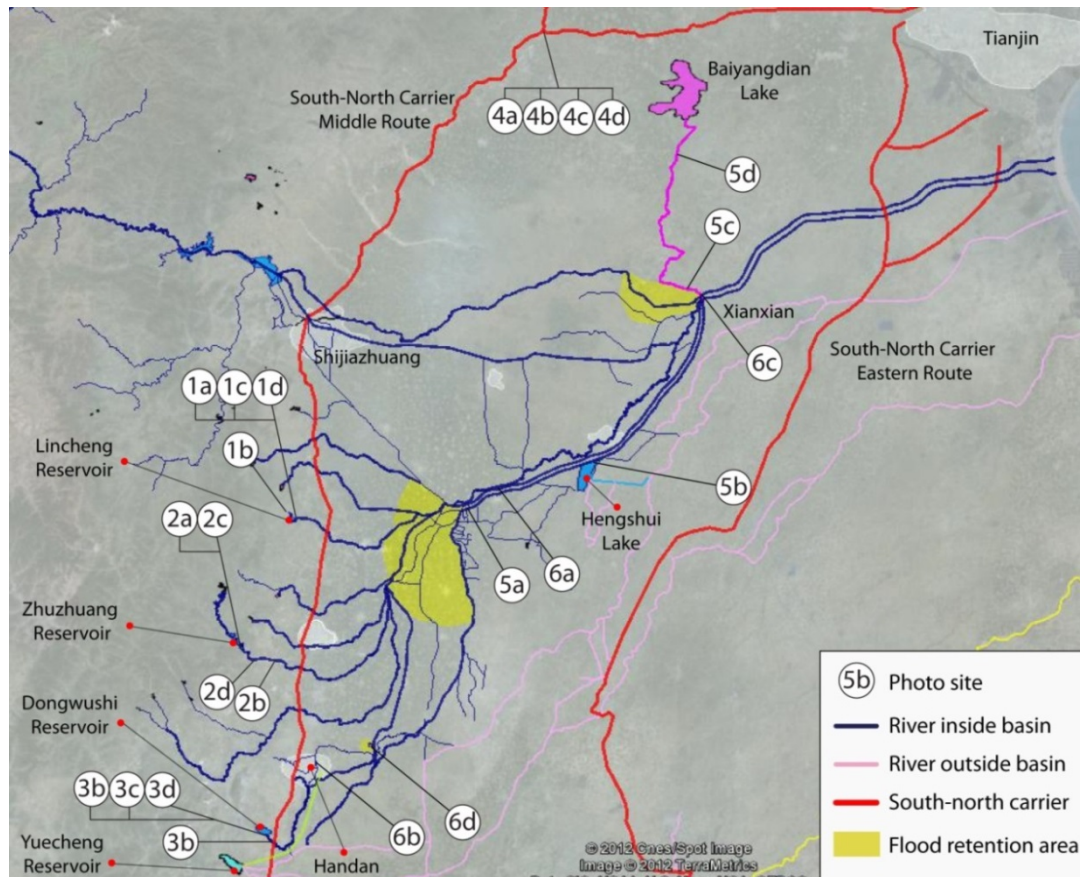


Figure 4: Overview of the Ziya River basin. The locations of all photos in the collages are indicated. Background map from Google Inc., (2013).

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Photos (1): Lincheng Reservoir. 1a) Tour boats in the park, 2b) inlet from the Taihang Mountains, 2c) Tour boats with the Lincheng dam in the background, 2d) Maize field in the Taihang Mountains



Photos (2): Zhuzhuang Reservoir. 2a) Flood gates and spillway, 2b) Quarrying in the river delta, 2c) View of the reservoir from the dam, 2d) Local people washing cars and motor bikes at the river crossing point.



Photos (3): Dongwushi Reservoir. 2a) Grey/white water in the Fuyang River, 2b) Control station close to the hydropower plant, 2c) Man feeding his fish, 2d) Overview of the aquaculture in the reservoir.



Photos (4): South-North Water Transfer Project at split point to Tianjin. 4a) Overview sketch, 4b) Basin 4c) the pipe, 4d) Inlet to the pipe (left) and inlet to the basin (right).

VI

Field Report 3, March 2013

Kristina Nowak Marker & Claus Davidsen

Field Report 3, March 2013

Authors: Kristina Nowak Marker & Claus Davidsen



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1 Introduction

From March 17-27, 2013 the Ziya River basin was visited with the scope of collecting data on particularly groundwater pumping, groundwater aquifer status and existing management practices. The field trip team was:

- Claus Davidsen, PhD student, DTU Environment and CAS IGSNRR
- Kristina Nowak Marker, MSc thesis student, DTU Environment
- Winda Zhao (John), English-speaking Chinese driver

The aim of this report is to document findings and experiences from the fieldtrip to Ziya River Basin (ZRB) conducted in March 2013. The information should be considered as and on to previous filed reports carried out by Claus Davidsen, hence river flows are not included unless changes has been observed or are relevant for documentation in the Mater Thesis project “Optimizing surface water and groundwater allocations in the Ziya River Basin (China) using Stochastic Dynamic Programming” by Kristina N. Marker, 2013. The report will support decision making considering model setup of a hydrological model used in the thesis as well as data for the optimization model. This field trip focused primarily on improving knowledge of:

- Agricultural water demands (primarily wheat and maize) and irrigation practice
- Estimated groundwater table
- Pumping costs for ground- and surface water
- Estimated distribution of ground- or surface water use
- Flow regime of rivers and lakes considered in the hydrological model
- Irrigation water released from the South-to-North Transfer Project

In total 22 farmer interviews were carried out throughout the ZRB catchment area. Out of these, 13 were located within or at the border of North China Plain, NCP, Figure 1. In the last sections of this report the questionnaire used and raw data obtained are shown.

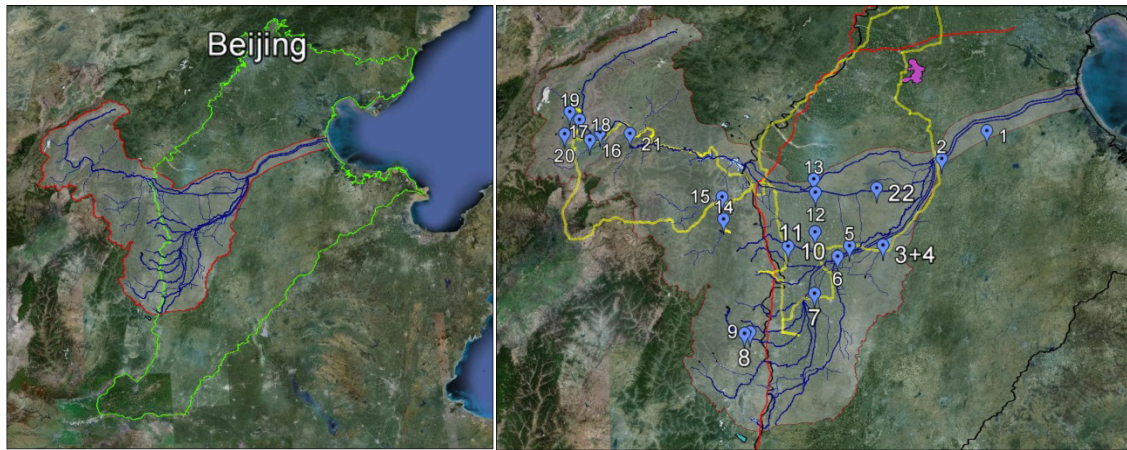


Figure 1: Study area. Left) NCP highlighted in Green, ZRB highlighted in red. Right) Zoom in on ZRB showing location for 22 farmer interviews as well as the field trip route shown in yellow. Background map: Google Earth, (version 7.1.2.2041), 2013.

2 Water use and demand

The Baiyangdian Lake is situated north of the ZRB and has over the past many years experienced a decreasing water table due to a reduced inflow caused by human abstractions. Diversions from ZRB have been made possible as seen on the previous field trips. At this visit, the water level in the Baiyangdian Lake seemed very high with surface water tables at or even a bit above what looked like the normal maximum capacity. A few old houses had water at the doorstep (see Figure 8b). This high water table could be a consequence of extreme rainfalls during the fall or the record breaking extreme rain experienced in Beijing in the summer of 2012.

The first round of irrigation was already initiated when the New Hutuo River was visited. During these irrigation periods, water is released from reservoirs into main canals (e.g. New Hutuo River) and from there delivered to the farmers through a network of irrigation channels. A manager, at the inlet point to the South-North Water Transfer Project, informed that 47 m³/s were being diverted from the Huangbizhuang Reservoir to irrigation downstream Shijiazhuang. This flow left the New Hutuo River channel full.

A general impression is that the surface water resource is extremely controlled; in some areas, water is only released in short periods (days, weeks) of time from the reservoir. Farmers living close to reservoirs or rivers will most likely use surface water for irrigation, as seen in Figure 2, where the irrigation water source for each farmer is shown.

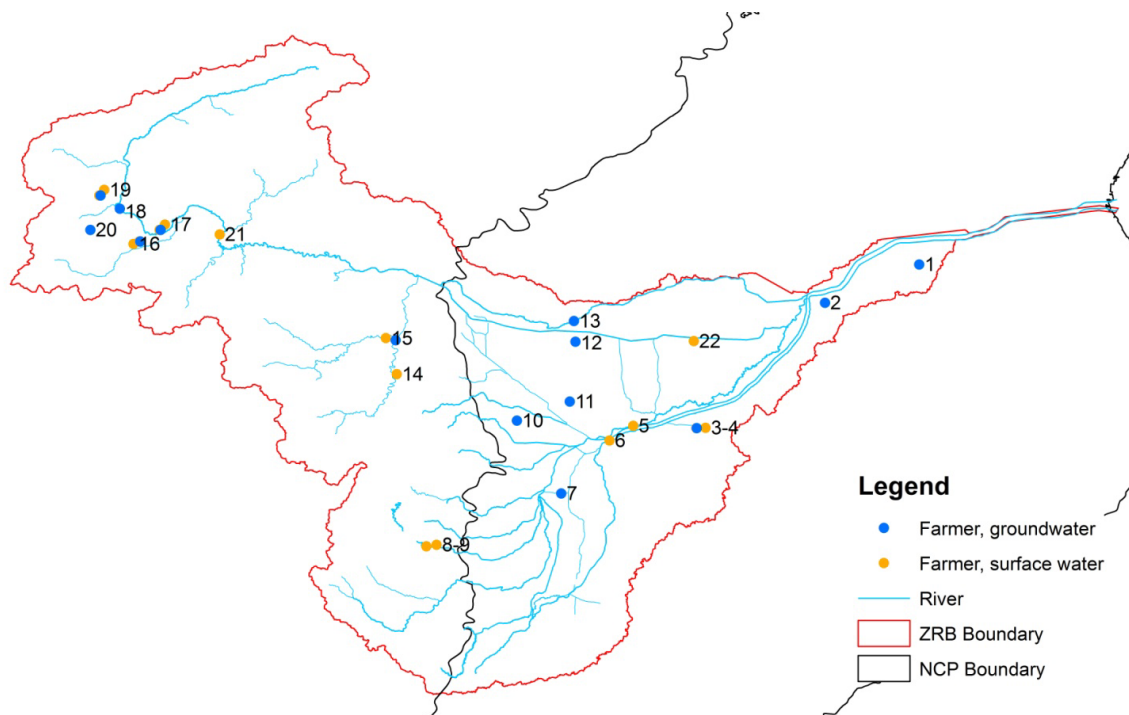


Figure 2: Illustration of surface water and groundwater usage by the 22 interviewed farmers. Blue circles indicate that crops are irrigated with groundwater, orange circles that crops are fed by surface water, e.g. reservoir or surface water pumping, and mixed indicate that farmers will use surface water when available and then shift to groundwater pumping.

The orange circles in Figure 2 show that farmers close to rivers only use surface water for irrigation. There are a few exceptions. Farmer 13 is located close to old Hutuo River, but since most water is now diverted into the New Hutuo River, these farmers now have to use groundwater. For farmer 18 it is more expensive to use surface water than groundwater – unlike the tendency seen for remaining farmers. Farmers located at a distance from rivers use either a mix of water sources, farmer 3, 4, 15, 16, 17, and 19, or groundwater only, indicated by blue circles on Figure 2.

All of the interviewed farmers pump drinking water from the deep groundwater aquifer; no surface water is used for drinking water purposes. If water is not pumped by the farmer or locally in the village, water is, e.g., supplied in water tanks (1 m^3) from a nearby village. In the mountain area villagers have been seen to dig large holes of up to 4 meters deep, which are used for additional water storage, Figure 9h.

2.1 Vegetation and Irrigation

The crop water demand depends highly on the crops grown, since the timing of plant growth varies with season. The main crop type in ZRB is summer maize and winter wheat in a crop rotation system (the same fields are used). Additionally, a large area with fruit trees (golden pears) was observed in the central part of ZRB, between farmer 11 and 12, Figure 10f, as well as cotton crops in the eastern part of ZRB. In the mountainous areas of ZRB, maize is the main crop. Due to a shorter growing season, wheat is normally not grown during the spring. Water is applied to sections of fields, which are flooded by up to 200 mm.

Small dikes around the plots contain the water and allow ponding until farmers manually allow water to flow into the next section by systematically making passages in the dikes, Figures 10a-10g. Surface water is either distributed onto fields directly from irrigation channels controlled by gates or pumped from rivers and applied to fields directly or distributed in the channels, Figure 8d-f and Figure 9a-b. The small tractors are widely used to drive these simple pumps. Groundwater can both be pumped by the individual farmer, Figure 9c-d, or locally in the villages, where it is then distributed to farmers. These pumps are driven by dedicated electric pumps.

Irrigation on the NCP takes place mainly in the dry spring where wheat production takes place. Farmers irrigate crops of wheat once a month for three months during March, April and May. In this period (1-2 weeks at a time) water released from the Huangbizhuang Reservoir for farmers using Hutuo River water. Otherwise the flow is cut off; see section about the South-to-North Water Transfer Project. At the time of this visit, the first irrigation period had just begun and water was being released from Huangbizhuang Reservoir distributed in channels and pumped from groundwater. In contrast, no similar releases from the Dongwushi and Zhuzhuang Reservoirs were noted.

Maize is sowed around June (start of rainy season) and depending on the precipitation between 0 and 3 irrigation applications are required. Irrigation will then take place in June (to prepare the fields), August and September. However, farmers expressed that maize is usually irrigated only once in the beginning of the growing season.

It was found that irrigation is normally carried out for 1 hour per mu (1/15 hectare), and water is applied until fields are flooded with up to 0.1-0.3 m of water. Some farmers explained that they use surface water whenever availa-

ble and then they switch to groundwater in the early summer when it is normally dry. Crops are primarily rain fed in the rainy season.

Some reports have indicated that the irrigation water demand for the same crop can vary according to location i.e. crops of wheat might need more or less irrigation in the coastal plain than in the piedmont plain. From the field study, there is no tendency indicating higher or lower irrigation practices for wheat or maize at the different locations. Irrigation patterns were very much alike across ZRB with average annual irrigation frequency four times for wheat, once for maize, and ten times for fruit trees adding up to an average annual water demand of 500 mm for combined wheat and crop and 500 mm for fruit trees.

The cost for surface water and groundwater varied significantly. A table showing the calculated demands and cost for each farmer is shown in section 7, table 3.

Besides availability of the water, also pollution played a big deal for the farmers. In some areas polluted water has proven to be harmful for plant sprouts, reducing crop output. This was experienced by farmer 7. Farmers also expressed their concerns of the polluted water and the health of their families. E.g. farmer 5 is forced to eat his own wheat production even though he knows he is using polluted surface water for irrigation. They are concerned for their health since more and more are getting ill, e.g., from cancer. They have a pump, but it is too difficult to use. Furthermore, the groundwater is very salty. Even though they pump from 200 m deep they claim that it is so salty that others would not like to drink it. However, they use this water as drinking water supply.

3 Estimated groundwater table

The groundwater table was found to be located approximately 10 – 100 meters below surface with a mean of 70 m, Figure 3, but with only farmer 3 and 4 indicating levels of up to 10 meters. The usable/drinkable groundwater zone is situated in 100-400 meters depth below surface, with mean of 215 m.

There is no clear tendency considering groundwater depth, except from, perhaps, a slightly decreasing groundwater level from east to west and from north to south (except from farmer 1, 3 and 4).

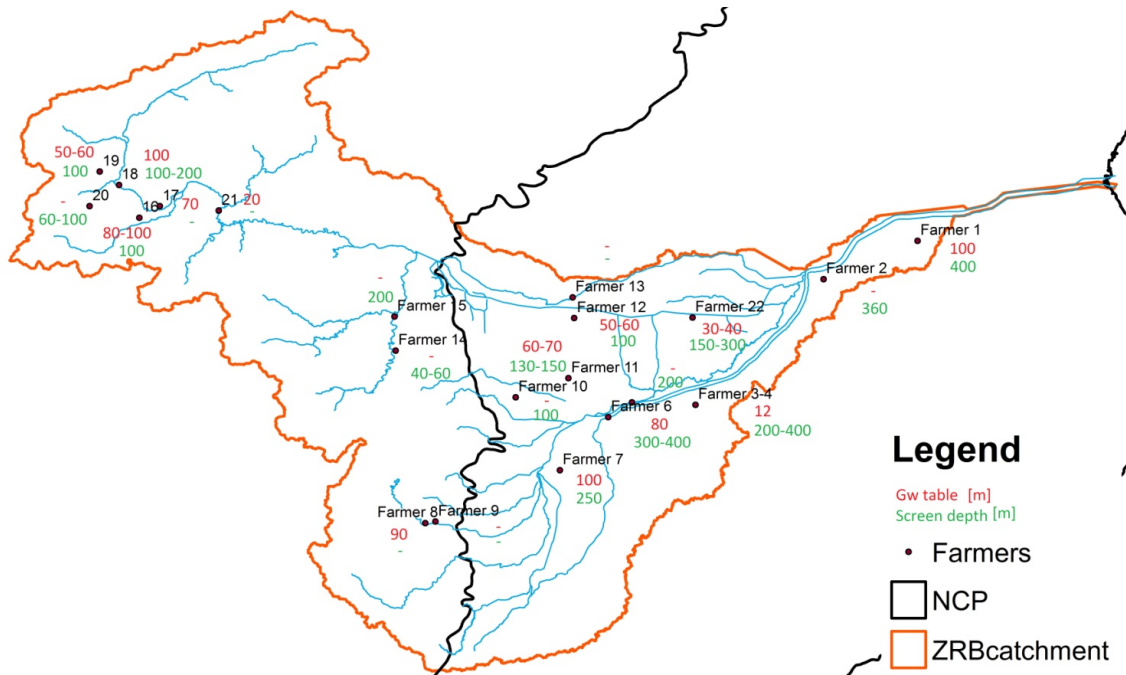


Figure 3: Indication of depth to phreatic surface (red) and depth of pumping (green). [-] is used in case of no data. Ziya River Basin stretches across the North China Plain (NCP) and continues into the mountains in the west. Gw = groundwater.

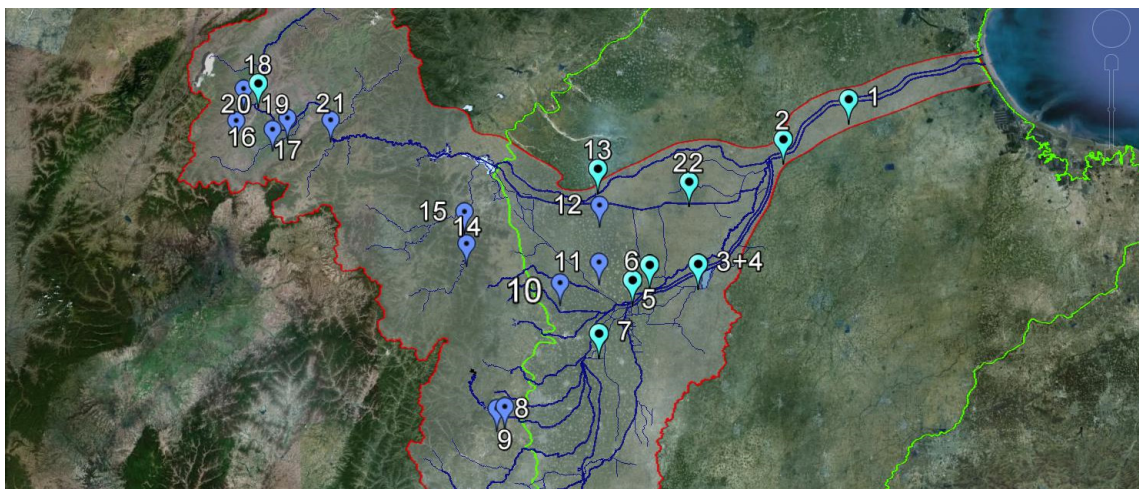


Figure 4: Light blue place markers indicate areas, where farmers have experienced saline top layers of ground water. The saline water reaches approximately 200 km into the plane. Background map: Google Earth, (version 7.1.2.2041), 2013.

The difference in groundwater table and screen depth is in most cases due to saline groundwater layers. Nine out of 22 farmers experienced issues with saline drinking water pumped from top ground water layers, Figure 4. The farmers experienced that the saline groundwater and the declining water table had worsened over time. Farmer 2 explained that in 1980, water was pumped from only 60 m depth compared to 360 m today. He explained that pumping

cost had increased and they now pay more to pump water due to the electricity cost. Farmer 2 also mentioned issues with fluoride in the water, which damaged their teeth. The farmer still continues to use groundwater, like other farmers in the area, since they are scared of the health consequences from using polluted surface water.

4 Pumping costs

Surface water is being utilized in areas close to rivers, whereas groundwater is used in remaining areas, Figure 2, except in the mountain areas, where both surface water and groundwater is used. In general surface water is less expensive than groundwater; hence farmers prefer to use surface water when available (releases from reservoirs or river flow in the rainy season). The distribution of cost and uses is shown in Figure 5.

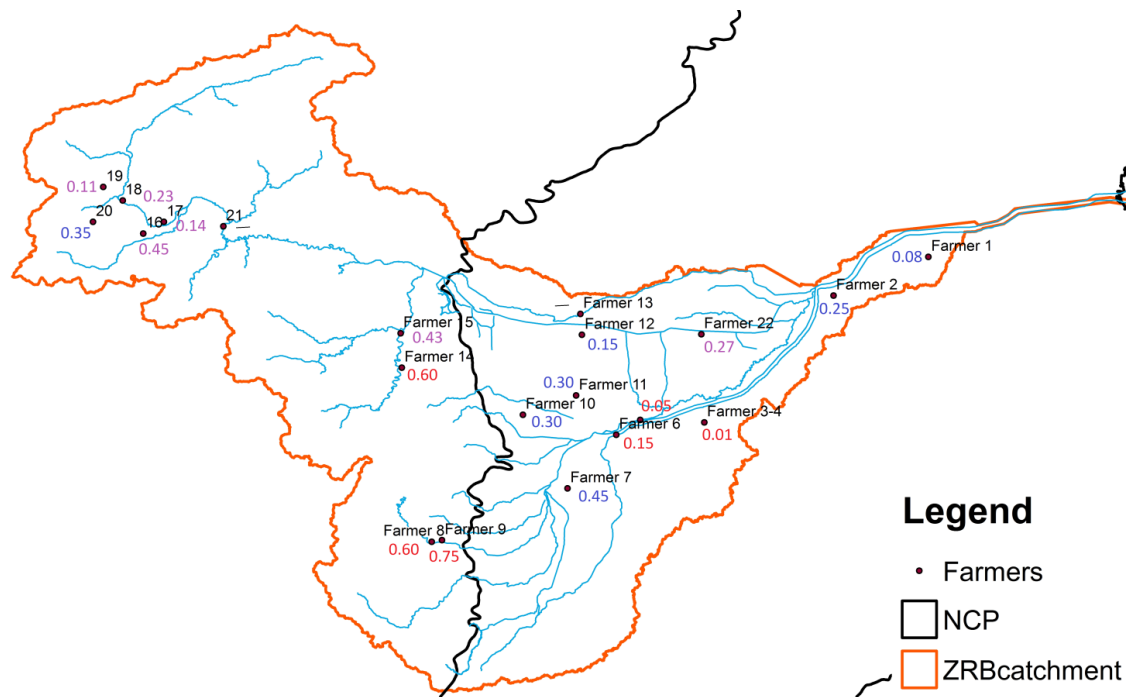


Figure 5: Groundwater and surface water use and the related costs in CNY/m³.

The cost of irrigating is almost entirely based on electricity/petrol costs/running cost of the pumps and tractors, which correspond to 10-40 CNY per irrigation. An average cost for both surface water and groundwater was estimated to be 0.20 CNY/m³ and 0.40 CNY/m³, respectively. The estimation is based on the given flooding depth, the area (most often 1 MU =

1/15 hectare) and the price that the farmer pays. Data are shown in section 7, Table 1-3.

Some farmers also pay for maintenance, manager fee, workers salary etc. This was the case for farmer 15 and 18. Farmer 18 pays a relatively high groundwater price compared to other farmers in the mountainous area. However, he estimates that surface water from Hutuo River and reservoirs are even more expensive. Farmer 18 explains that the institutional setup makes it costly to use surface water for farmers. The cost covers manager and worker salary, pumping expenses, maintenance of pumps, dikes and gates, amongst others. Therefore groundwater is cheaper and he can use it when he wants. For farmer 16 nearby, surface water from the reservoir has the same price as groundwater, and therefore they use both sources of water. As farmer 18, he finds it a benefit that the groundwater is available at all times, whereas surface water flows are controlled by the reservoir manager.

5 Rivers and Lakes

Even though some rivers had high water levels, others were completely dry (Old Hutuo River) or with no flow (Old Fuyang River and Tzu-ya river to Tianjin was filled with water but had no observable flow) indicating a highly controlled river system. In the following, a short review of observations made of main rivers in ZRB.

5.1 Hutuo River

Old Hutuo river was found to be dry – some places ponding but with no flow. Water is directed from Shijiazhuang upstream and into New Hutuo River instead, which converge with Fuyang River. The flow was 36 m³/s in New Hutuo River. Water is diverted from Shijiazhuang into New Hutuo River, which again diverts water further into irrigation canals (the two vertical rivers between Hutuo He, farmer 12, and Fuyang He, farmer 5) during periods of irrigation. At the confluence point with Fuyang River, the river is nearly empty.

A farmer explained that he, by mail, is notified about scheduled irrigation releases for his area ahead of the growing season. A series of local water managers will divert water from the main rivers and eventually all the way to the individual farmers.

Upstream Hutuo River, in the Taihang Mountains, an estimated flow of 10 m³/s was observed. It is noticed that there are significant daily fluctuations, probably due to irrigation taking place in the morning until noon. No visible pollution could be observed in the Hutuo River upstream Gangnan Reservoir.

5.2 Gangnan and Huangbizhuang Reservoirs

The Gangnan Reservoir had a significantly higher storage than observed at field trip 1. The water level was estimated 10-20 meters higher. The water was clear and multiple locals were swimming in the water.

5.3 Fuyang River

Old Fuyang River had no flow in the downstream section close to the confluence point, and a dike had been made across the river in Hengshui, Figure 15. The river floor is permeable clay material and not human made concrete.

The New Fuyang River in the area of Hengshui also had no flow at the time of visit. Construction work was ongoing at the bridge of road 391, and no water could cross at this point. With both the New and Old Fuyang Rivers being cut close to each other, any flow would pass through Fu Dongpai River (the third river). It therefore follows that the low flow observed in Ziya River, downstream the confluence point, must be a combination of the low flow observed in the Fu Dongpai River and unused irrigation water from the New Hutuo River.

At the confluence point, blue foam was forming in the black and strongly smelling water. A guess is that the blue color is waste water from a Hengshui industry, e.g., the locals talked about an ink producer. In Hengshui, the Old Fuyang River was heavily polluted, and waste water could be observed leaching into the river. At all sites along these three Fu Rivers, black and strongly smelling water could be observed.

Upstream Hengshui, farmers were once again using this heavily polluted water for irrigation (see Figure 10 c and e). As stagnant water was pumped from the Old Fuyang River, white foam was formed in the black water. No signs of the downstream blue foam could be observed.

5.4 Baiyangdian Lake

The Baiyangdian Lake is located north of the Ziya River Basin. It has great importance for tourism, Figure 8a, lotus flower harvest, fishing, Figure 8c

etc. The lake is natural, hence exchange with groundwater and influence on ground water table expected.

5.5 Hengshui Lake

Hengshui Lake is located upstream the confluence point (close to farmer 3 and 4). The lake is used for storage of drinking water and also acts as a recreational area with park facilities, nature reserve for birds and fish. The water table is stable throughout the year. Once every year, water from the yellow river is supplied to Hengshui Lake.

5.6 South-to-North carrier

In spring, the Gangnan reservoir in Shijiazhuang provides water to New Hutuo River for a short period of approximately two weeks at the time to allow downstream farmers to utilize water for irrigation. At the time of visit (20-22nd of March), 47 m³/s of water was released from the Gangnan reservoir. From this 36 m³/s continued into New Hutuo River and 11 m³/s were diverted into the carrier as presented in Figure 6. Out of the 11 m³/s, 5 m³/s was diverted into Old Hutuo River to use for wheat production downstream and 6 m³/s continued to Beijing through the carrier, Figure 11e-f. This was an agreement made between the province and the carrier managers. The province simply rent some spare capacity in the carrier to supply some of the farmers a few days. Outside this period, the New Hutuo River receives no water for irrigation purposes and any releases into the canal are diverted to Beijing.

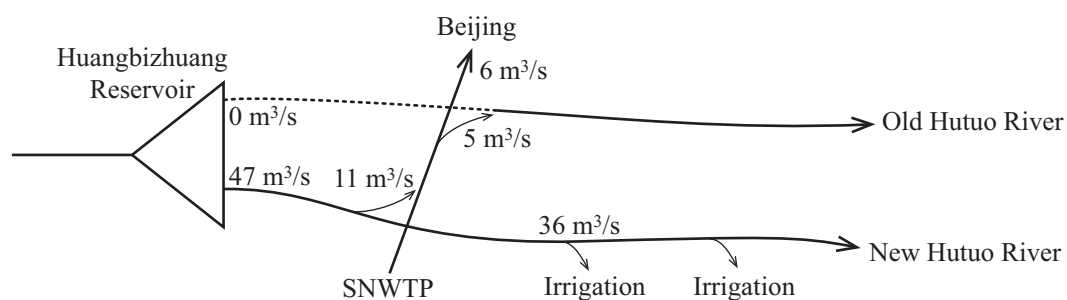


Figure 6: Illustration of water management from Gangnan reservoir and to Hutuo He through the South-to-North water transfer project, SNWTP.

The water quality at this point looked good. No smell and the water were only slightly colored by mud. Beijing receives water from the carrier during the winter months. During the rainy summer season, it is not necessary to divert

water to Beijing. The operation of the gate, where water is diverted, is not managed by a certain schedule; instead managers contact the carrier manager and ask for water.

It was noticed that the water flow was highly reduced in New Hutuo River at the confluence point where it meets Fuyang River. It is therefore expected that water released from the Huangbizhuang Reservoir is used for irrigation along the river.

6 Farmer data

Table 1, 2 and 3 presents the data collected through the field interviews.

Table 1: Farmer ID (see Figure 2), water sources, depth to groundwater and depth to un-saline groundwater experienced by farmers, where sw is surface water and gw is ground-water.

ID	Source	SW source	Crop	Depth to gw m	Depth to unsaline water m	Saline top layer	Note
1	gw		Fruit trees	100	400	yes	#1
2	gw		Wheat/maize		360	yes	#2
3+4	sw	Fu Dongpai	Wheat/cotton	12	200-400	Yes	
3+4	gw/sw	Fu Dongpai	Wheat/maize			(Yes)	
5	sw	Old Fuyang	Wheat/maize		200	Yes	
6	gw	New Fuyang	Wheat/maize	80	300-400	yes (little)	#3
7	gw		Wheat/maize	100	250	Yes	#4
8	sw	Zhuzhuang R.	Wheat/maize	90		No	
9	sw	Zhuzhuang R.	Wheat/maize			(No)	
10	gw		Wheat/maize	100	100	No	
11	gw		Wheat/maize	60-70	130-150	No	
12	gw		Fruit trees	50-60	100	No	
13	gw		Wheat			Yes	
14	sw	Ziya River	Maize	40-60	40-60	-	
15	gw/sw	Ziya River	Maize	200	200	-	
16	gw/sw	Reservoir	Maize	80-100	100	-	
17	gw/sw	Hutuo He	Maize	70		-	
18	gw		Maize	100	110-200	Yes	#5
19	gw/sw	Reservoir	Maize	50-60	100	No	
20	gw		Maize	60-100	60-100	No	
21	sw	Reservoir	Maize	20		No	
22	sw	Huangbizhuang R. & Gangnan R.	Wheat	30-40	150-300	Yes	

#1 The farmer reported 300 - 400 m to drinking water.

#2 In 1980s gw table was 60 m.

#3 Farmer reported that 20 - 30 years ago the water quality was much better.

#4 Farmer reported 200-300 m to drinking water.

#5 Could use surface water from Hutuo He but this is normally more expensive than groundwater.

Table 2: Water demands and irrigation practice reported by the farmers. R = rainfed, irrigation of other crops than wheat or maize are marked with ‘-’.

ID	Irrigation applications #1		Irrigation frequency		Annual irrigation (mm/year)		
	Maize	Wheat	Maize	Wheat	Lower	Upper	Average
1 #2			-	-	-		
2	-	20-30cm x3		3	600	900	750
3+4	-	30cm x4		4	1200	1200	1200
3+4	-	20-30cm x4		4	800	1200	1000
5	10cm x2-4	10cm x3	2-4	3	500	700	600
6	20cm x1	20cm x2-3	1	2-3	600	800	700
7	10cm x1-2	10cm x3	1-2	3	400	500	450
8	10cm x2	10cm x3	2	3	500	500	500
9	rainfed	10cm x3	R	3	300	300	300
10	10cm x0-2	10cm x3	R-2	3	300	500	400
11	10cm x0-1	10cm x2-3	R-1	2-3	200	400	300
12 #3	-		-	-	500	1100	800
13	-	x6-7		6-7	-	-	-
14	10-15cm x5-10	-	5-10		500	1500	1000
15	10cm x2	10cm x3	2	3	500	500	500
16	10-15cm x1	-	1		100	150	125
17	20-30cm x2	-	2		400	600	500
18	10cm x2-3	-	2-3		200	300	250
19	30cm x2-3	-	2-3		600	900	750
20	10-20cm x3-4	-	3-4		300	800	550
21	10cm x5	-	5		500	500	500
22	20-30cm x0-1	20-30cm x2	R-1	2	400	900	650

#1 Explanation: **10cm x2-4** is irrigation until 10 cm ponding water on the field, 2-4 times per year.

#2 20-30 cm irrigation of other crops than wheat and maize.

#3 5-10cm x10-11 irrigation on other crops than wheat and maize.

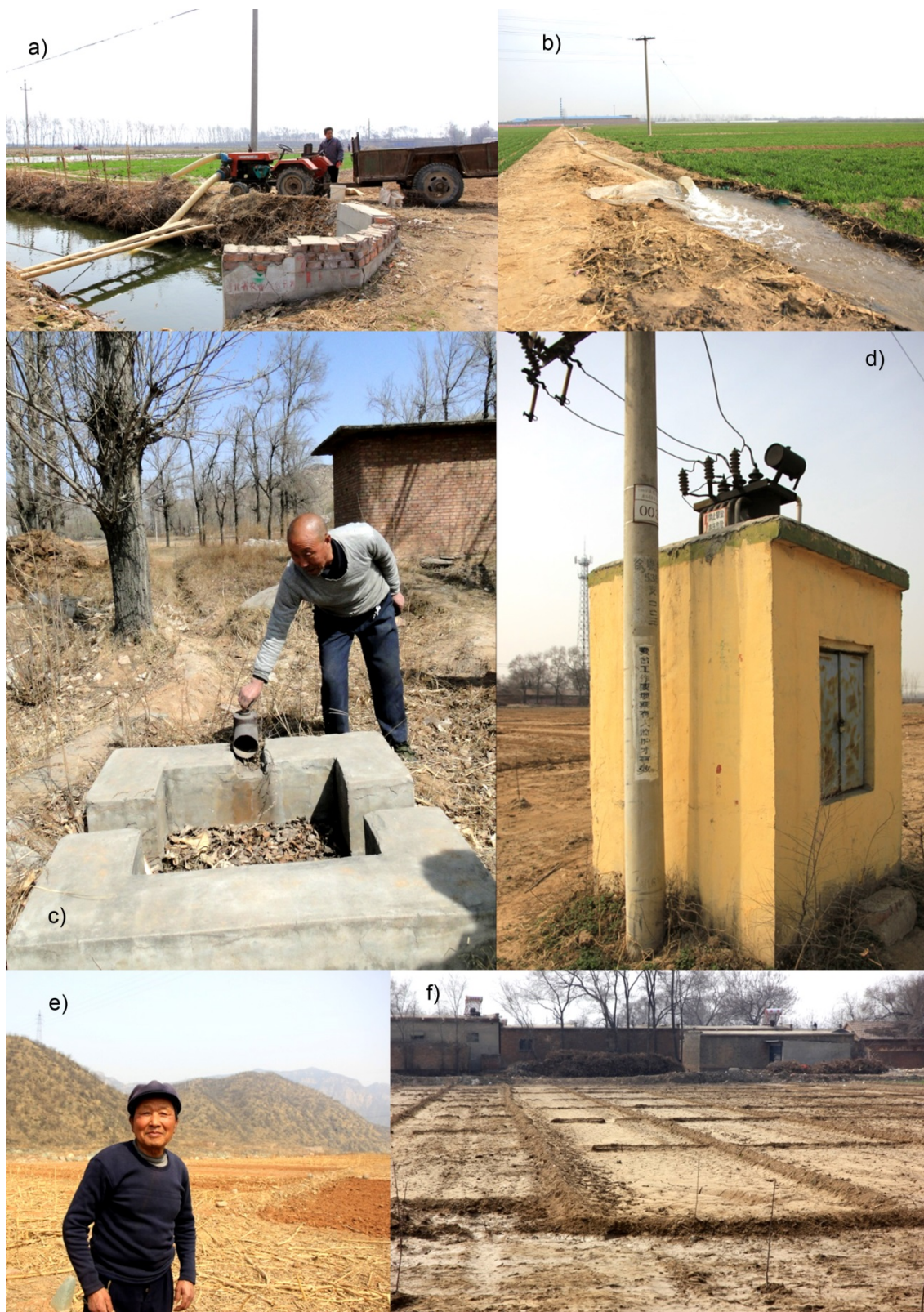
Table 3 shows the estimated average annual irrigation demand and the cost to use groundwater or surface water for irrigation for each farmer. The total annual irrigation demand was estimated to 500 mm for combined wheat and crop and 500 mm for fruit trees. This estimation is based on a demand of four times 100 mm for wheat, one times 100 mm for maize and 10 times 50 mm for fruit trees. The cost of groundwater and surface water irrigation to fulfil the above demand was estimated to 0.4 Yuan/m³ and 0.2 Yuan/m³, respectively.

Table 3: Demand, irrigation frequency and cost of water estimated for each farmer, where E indicates that the farmer pays only for electricity and M indicates additional payment to a manager for maintenance, operation, salary etc.

ID	Groundwater cost [Yuan/m ³]	Surface water cost [Yuan/m ³]	Pump depth [m]	Payment	Longitude	Latitude
1	0.075		100	E	38.350	116.623
2	0.25			E	38.165	116.167
3+4		0.01	12	E	37.556	115.546
3+4				E	37.556	115.546
5		0.05		E	37.567	115.239
6		0.15	80	E	37.496	115.124
7			100+	E	37.239	114.890
8		0.6	90	E	36.983	114.237
9				E	36.990	114.286
10				E	37.592	114.675
11			60-70	E	37.685	114.931
12	0.15		50-60	E	37.976	114.958
13		-		E	38.076	114.951
14		0.6		E	37.818	114.093
15	0.6	0.25		M	37.983	114.088
16	0.45	0.45	80-100	E	38.462	112.852
17	0.18	0.09	70+	E	38.518	112.950
18	0.15	0.3	110	E	38.621	112.753
19	0.15	0.06	50-60	E	38.686	112.659
20	0.35			M	38.518	112.610
21	0		20	E	38.497	113.236
22	0.27	0.27	30-40	E	37.979	115.532



Photos 1: a) Tourism at Baiyangdian Lake. b) Water Levels are high at Baiyangdian Lake. c) Fishery in Baiyangdian Lake. d) Surface water pumping at New Fuyang River e) Surface water pumping. Water from the pump house is diverted into the water channel in Figure f. f) Distribution channel.



Photos 2: a) Surface water pumping b) Irrigation water distributed to irrigation channel. c) Farmer showing his groundwater pump. d) Pump house. e) Farmer preparing his maize fields in the mountains. f) Division of fields into sections, ready for irrigation.



Photos 3: a) Farmer letting water through dike to irrigate the next wheat crop. b) The irrigation channel runs along all the crops allowing irrigation of crops one by one. c) A wheat field being flooded with black water from the Old Fuyang River. d) Farmers supervising irrigation. e) Polluted irrigation water distribution channels on either side of the road. f) Peach trees. g) Flooded wheat plants. h) A family builds additional water storage by digging a large hole.



Photos 4: a) Tzu-ya River with high water table but no flow. b) Diversion of irrigation water at Hutuo Reiver into irrigation rivers c) New Hutuo River, upstream d) Irrigation river section between Hengshui and Fu DongPai. e) Part of the South-to-North carrier at the diversion in Shijiazhuang. f) Construction of the South-to-North Transfer project. g) The Gangnan Reservoir at Shijiazhuang as seen during field trip 1 in June 2012 and h) again in March 2012.

The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within four sections:

Water Resources Engineering, Urban Water Engineering,
Residual Resource Engineering and Environmental Chemistry & Microbiology.

The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

DTU Environment
Department of Environmental Engineering
Technical University of Denmark

Miljoevej, building 113
2800 Kgs. Lyngby
Denmark

Phone: +45 4525 1600
Fax: +45 4593 2850
e-mail: info@env.dtu.dk
www.env.dtu.dk